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THE ROAD LESS TRAVELED: NEW CHEMISTRY OF
OLD REACTIVE INTERMEDIATES

BY

ERIN CARCELLA MCLAUGHLIN
B.S., Bridgewater State College, 2009

THESIS

Submitted to the University of New Hampshire
in Partial Fulfillment of
the Requirements for the Degree of

Master of Science
in
Chemistry

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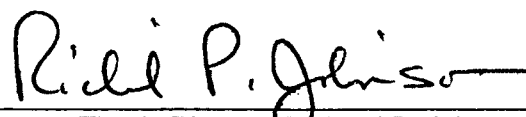
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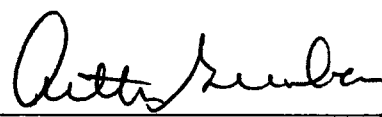


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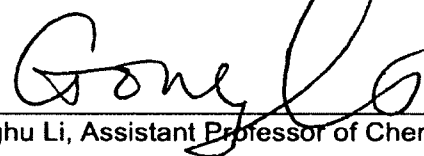
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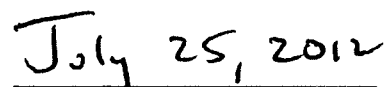
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Date

DEDICATION

To my loving, patient
and always encouraging parents - Ann and Doug.

TABLE OF CONTENTS

	PAGE
DEDICATION.....	iii
LIST OF SCHEMES.....	viii
LIST OF FIGURES.....	x
LIST OF TABLES.....	xi
ABSTRACT.....	xii
 GENERAL INTRODUCTION.....	 1
 CHAPTER	
I. NEW SYNTHETIC UTILITY OF BENZYL ALCOHOLS IN MICROWAVE-ASSISTED ELECTROPHILIC AROMATIC SUBSTITUTION	
Introduction.....	2
Alternative Substrates.....	3
Catalytic Studies.....	4
Project Goals.....	7
Microwave Synthesis.....	7
Results and Discussion.....	8
Initial Experiments.....	8

	Anhydrous iron (III) chloride vs. iron (III) chloride hexahydrate.....	10
	Optimization of Reaction Conditions.....	11
	Acetates as Substrates.....	12
	Applications Towards Cyclophane Synthesis.....	14
	Conclusions and Future Work.....	15
II.	SOLUTION PHASE ROUTES TO <i>ORTHO</i> -XYLALLENE	
	Introduction.....	16
	<i>ortho</i> -Xylylene: A Reactive and Versatile Intermediate.....	16
	<i>ortho</i> -Xylallene.....	17
	Current Routes to <i>o</i> -xylylene.....	19
	Project Goals.....	20
	Results and Discussion.....	20
	Attempted Routes to <i>ortho</i> -xylallene: 1,4-Elimination.....	20
	Cheletropic Extrusion of Sulfur Dioxide.....	22
	S _N 2' Hydride Addition.....	23
	Conclusions and Future Work.....	25
III.	INTERCONVERSIONS OF SUBSTITUTED ARENES VIA <i>IPSO</i> ARENIUM IONS	
	Introduction.....	26
	Substituent Migration in <i>Ips</i> o Arenium Ions.....	26
	Understanding the Mechanism for Rearrangement.....	28
	An Old Rearrangement of Terphenyl Rediscovered.....	29
	Goals of the Present Research.....	29
	Results and Discussion.....	30

Establishment of an Acid Catalyzed Isomerization.....	30
Microwave-Assisted Rearrangements.....	32
Reaction Mechanism and Correlation with Computations.....	33
Optimization of Reaction Conditions: Higher Acid Concentrations.....	36
Conclusions and Future Work.....	38
IV. EXPERIMENTAL	
General Experimental Section.....	40
Detailed Experimental Section.....	42
Chapter I.....	42
Chapter II.....	47
Chapter III.....	51
LIST OF REFERENCES.....	57
APPENDICES.....	63
Appendix A: Spectra.....	64
1,4-bis(hydroxymethyl)benzene diacetate (2).....	65
1,4-bis(phenylmethyl)benzene (3).....	67
1-acetoxy-1,1-diphenyl-methane (4).....	69
9-acetoxyfluorene (5).....	71
1,2,3,4-tetrahydro-naphthalen-1-yl acetate (6).....	73
9-acetoxyanthracene (7).....	75
1-indanylacetate (8).....	77
cyclohexyl acetate (9)	79
2-butyn-1,4-diol diacetate (11)	81
triphenylmethane (12)	83

1-(1-bromoethenyl)-2-methyl benzene (22).....	85
2-(2-bromophenylmethoxy)tetrahydro-[2 <i>H</i>]pyran (24).....	87
2-(acetoxymethyl)phenyl acetylene (25).....	89
tert-butyl(2-ethynylbenzyloxy)dimethylsilane (26).....	91
2-phenylnaphthalene (27).....	93
1,2'-binaphthalene (28).....	95
2,2'-binaphthalene (29).....	97

LIST OF SCHEMES

NUMBER		PAGE
1	AlCl ₃ mediated alkylation of benzene performed by Friedel and Crafts.....	2
2	Alcohol substrates offer formation of water.....	3
3	Proposed mechanistic pathways.....	4
4	Sc(OTf) ₃ -catalyzed arylation reaction of aromatics with benzyl alcohols.....	5
5	Reaction of <i>o</i> -xylene with 1-phenylethyl acetate.....	5
6	Benzylation of methyl benzyl ether.....	6
7	Arylation of 2-bromobenzyl alcohol by conventional heating.....	6
8	Diphenylmethane synthesis.....	9
9	Microwave-assisted benzylation of benzene.....	11
10	Acylation of 1,4-bis(hydroxymethyl)benzene.....	12
11	Synthesis of 1,4-bis(phenylmethyl)lbenzene via diacetate.....	12
12	Synthesis of <i>meta-para</i> -cyclophane.....	15
13	Pyrolysis of indene.....	16
14	Pyrolysis of <i>o</i> -ethynyl toluene.....	17
15	Proposed routes to <i>ortho</i> -xylallene.....	17
16	Dimerization of <i>ortho</i> -xylallene to chrysene.....	18
17	Microwave-flash pyrolysis of <i>o</i> -ethynyl toluene.....	18
18	The most efficient pathways for generation of <i>o</i> -quinodimethanes as classified by Segura and Martín.....	19

19	Routes to <i>ortho</i> -xylallene via (a) base induced or (b) metal or ion-catalyzed 1,4-elimination.....	21
20	Proposed synthesis by base-catalyzed (a) and ion-catalyzed (b) 1,4-elimination pathways.....	21
21	Formation of <i>ortho</i> -xylylene and <i>ortho</i> -xylallene by thermal elimination of SO ₂	22
22	Formation of <i>o</i> -xylallene via allene synthesis.....	23
23	Activation of <i>o</i> -ethynylbenzyl alcohol and treatment with NaBH ₄	24
24	Major formation of <i>meta</i> -substituted products reported by Baddeley and Kenner.....	26
25	The effect of aluminum (III) chloride on 1,3-dimethyl-4-butylbenzene.....	27
26	Isomerization of <i>ortho</i> -terphenyl as shown by Allen and Pingert.....	27
27	Proposed mechanism for the acid-catalyzed rearrangement of 1,4-diethylbenzene.....	28
28	Product mixture recovered from attempted Scholl reaction.....	29
29	Isomerization to <i>meta</i> -terphenyl via treatment with excess AlCl ₃	30
30	Analagous results achieved with AlCl ₃ and TFSA in microwave.....	31
31	Rearrangement of 1-phenylnaphthalene with TFSA in the microwave.....	32
32	Rearrangement of 1,1'-binaphthalene to 2,2'-binaphthalene.....	32
33	Synthesis of 1,2-binaphthalene (28).....	33
34	Terphenyl cations by which substituent migration can occur.....	34
35	Energy surface for terphenyl rearrangement.....	35
36	Formation of fluoranthene from 1-phenylnaphthalene.....	37
37	Formation of perylene from 1,1'-binaphthalene.....	38

LIST OF FIGURES

NUMBER		PAGE
1	Iron (III) chloride species, anhydrous (I) and hexahydrate (II).....	10
2	Visualization of spin density on <i>o</i> -ethynylbenzyl acetate using ETM.....	24
3	Chromatogram of 1,1'-binaphthyl treated with 1.1M TFSA for 30 minutes at room temperature.....	33

LIST OF TABLES

NUMBER		PAGE
1	Arylation of benzene with methyl benzyl ether under various catalytic conditions.....	6
2	Acyl derivatives of respective alcohol substrates.....	13
3	% Yield of acetate and alcohol substrates under optimized conditions.....	14
4	Thermal elimination via cheletropic extrusion of sulfur dioxide.....	23
5	Conditions attempted for <i>ortho</i> -xylallene using sodium borohydride	25
6	Various conditions attempted to optimize isomerization	31

ABSTRACT

THE ROAD LESS TRAVELED: NEW CHEMISTRY OF
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by

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University of New Hampshire, September, 2012

Conditions were optimized to utilize benzyl alcohol and acetate substrates in Friedel-Crafts electrophilic aromatic substitution reactions. Anhydrous iron (III) chloride (20 mol%) was shown to be an efficient catalyst when using benzene in a microwave reactor. Rapid reactions and minimal further purification make this procedure suitable for chemical library generation. We attempted to develop a synthetic route to the little known intermediate, *ortho*-xylallene. Though work to date has been unsuccessful, we have determined that traditional routes via allene formation may be viable. Rearrangements of terphenyls, phenyl-naphthalene, and 1,1'-binaphthalene by ipso-arenium cations were studied using triflic acid in 1,2-dichloroethane. Preferred formation of *meta* products appears to be the result of low energy cations involved in rearrangement. Formation of Scholl-type products under these conditions provides evidence for a closely related carbocationic mechanism for the Scholl Reaction.

GENERAL INTRODUCTION

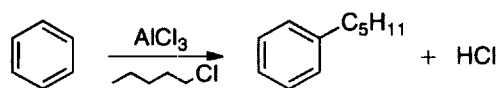
This thesis is separated into three separate chapters: 1) New synthetic utility of benzyl alcohols in microwave-assisted electrophilic aromatic substitution; 2) Solution phase routes to *o*-xylylallene; 3) Interconversions of substituted arenes via *ipso* arenium ions. Each chapter is self-contained with its own introduction, results and discussion, and conclusion.

CHAPTER I

NEW SYNTHETIC UTILITY OF BENZYL ALCOHOLS IN MICROWAVE-ASSISTED ELECTROPHILIC AROMATIC SUBSTITUTION

Introduction

The alkylation of benzene was first achieved through the use of amyl chloride and aluminum (III) chloride (AlCl_3) by Charles Friedel and James Mason Crafts in 1877 (Scheme 1).¹



Scheme 1. AlCl_3 mediated alkylation of benzene performed by Friedel and Crafts.

Now known as the Friedel-Crafts alkylation, this methodology was one of the first organic reactions to involve a Lewis acid. The Friedel-Crafts reaction remains the preferred method in organic synthesis for alkylation and acylation of arenes.² Standard conditions, however, generally require toxic alkyl halide substrates and stoichiometric Lewis or Brønsted acids, which make this methodology undesirable.³⁻⁶ In more recent years, efforts have been made to design more environmentally benign syntheses.^{5,7-9}

Our research currently includes the development of such conditions. By applying microwave radiation we also look to improve upon reaction times for current procedures, typically 3-24 hours for a Friedel-Crafts reaction.^{3,5,9-12}

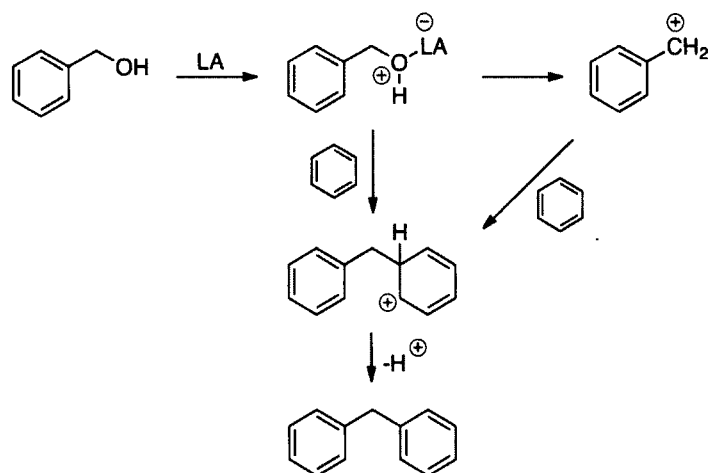
Alternative Substrates

Alkyl halides are inherently more reactive in electrophilic aromatic substitution; however, these substrates produce harmful and corrosive byproducts. Corresponding alcohols are more readily available, and formation of water would offer a more “green” chemical procedure (Scheme 2).



Scheme 2. Alcohol substrates offer formation of water.

Preparatory advantages have made alcohols more desirable substrates compared to alkyl halides for many years. Benzylic alcohols have been shown to be especially efficient when compared to primary, secondary or tertiary alcohols, presumably due to additional stabilization of the Lewis acid-complex (a nascent carbocation) by the adjacent aromatic ring.^{5,13-15} As the Lewis acid forms a complex with the oxygen atom, the α -carbon becomes activated as an electrophile (Scheme 3). Whether this complex dissociates to form a free cation in solution is unclear; identical products would form by either pathway.

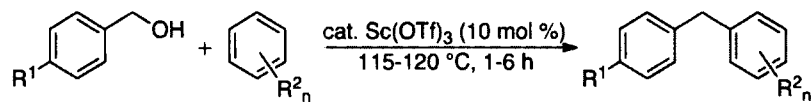


Scheme 3. Proposed mechanistic pathways.

Catalytic Studies

In Friedel-Crafts reactions, the traditional catalyst aluminum (III) chloride, must be used in excess and is destroyed during subsequent product recovery. This results in a poor atom economy as well as large volumes of acidic aqueous waste. AlCl_3 is known to react violently with water, thus limiting the scope of preferred solvents to carbon disulfide, dichloromethane and benzene, all known to be hazardous. Extensive efforts have been made to develop alternative catalysts that possess Lewis acidic properties but lack the environmental disadvantages and hazards of AlCl_3 . Lanthanide triflates were considered a large breakthrough in this field,¹⁶ as they allowed for catalytic reactions in aqueous media. These catalysts can be recovered easily which makes for an increasingly sustainable reaction.²

Fundamental research in this area began when Tsuchimoto and coworkers investigated the reaction of benzyl alcohols with catalytic scandium (III) triflate (Scheme 4).^{6,12} Upon reflux in benzene, a 91% yield of the alkylated product, diphenylmethane, was achieved.¹² In 1997 their work expanded to include aldehydes, acetals and allyl alcohols as efficient alkylating agents, using scandium (III) triflate as the catalyst.⁶

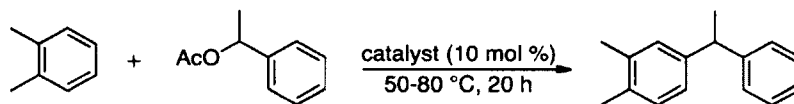


Scheme 4. Sc(OTf)₃-catalyzed arylation reaction of aromatics with benzyl alcohols.

Unfortunately, the rare earth metals that comprise these catalysts are costly; their production itself also may be polluting and hazardous.² As such, triflate catalysts are relatively higher in cost when compared to traditional catalysts, which are inexpensive and widely available.^{2,11,16,17}

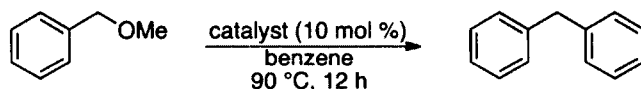
Though advances have been made through the use of benzylic alcohols, the catalyst and solvent conditions reported to date leave room for improvement. As stated, AlCl₃ is not favorable due to environmental concerns, while lanthanide triflates can be costly.¹⁸ Research on other catalytic systems has been reported. Catalysts such as Lewis acids (IrCl₃, RhCl₃),^{9,19,20} Brønsted acids (HCl, *p*-TsOH, H₂SO₄),^{14,15,20} transition metal triflates,^{6,12,13} H-montmorillonite clay^{3,21,22} and molecular iodine^{2,23} have been described. Cost and inherent toxicity render some catalysts undesirable for environmentally conscious syntheses. Iron (III) is abundant in nature, making costs low, and has been reported as an efficient catalyst for arylation.^{24,25}

In 2005, Iovel *et al.*¹⁵ examined the efficiency of a variety of Lewis and Brønsted acids in the reaction of *o*-xylene with 1-phenylethyl acetate (Scheme 5). Iron (III) chloride catalysts (FeCl₃, FeCl₃•6H₂O, Fe(ClO₄)₃•H₂O) provided yields of >99%, with high regioselectivity (>99:1).



Scheme 5. Reaction of *o*-xylene with 1-phenylethyl acetate.

lovel and coworkers continued their work with FeCl_3 to include alkylations with benzyl alcohols, benzyl acetates and benzyl carboxylates. Catalytic studies reported by Wang *et al.* in 2008⁵ further established iron (III) chloride as the most efficient Lewis acid catalyst for Friedel-Crafts arylation of benzyl methyl ethers (Scheme 6, Table 1). As seen in Table 1, a significant increase in percent conversion and yield was observed with iron (III) chloride when compared to aluminum (III) chloride.

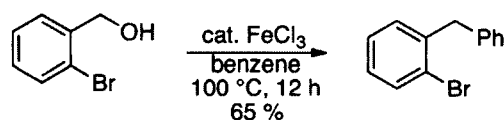


Scheme 6. Benzylation of methyl benzyl ether.

Table 1. Arylation of benzene with methyl benzyl ether under various catalytic conditions.⁵

Catalyst	Conversion (%)	Yield (%)
AlCl_3	<5	<5
$\text{Fe}(\text{OAc})_2$	<5	0
FeCl_3	>99	83
InCl_3	<5	<5
AuCl_3	12	12
HOTf	<5	0
HCl	<5	0

Based on the same considerations, Odedra, Datta and Liu¹⁰ carried out the catalyzed arylation of 2-bromobenzyl alcohol under thermal conditions in a sealed tube using anhydrous iron (III) chloride (Scheme 7). The product was purified by column chromatography and isolated in 65 % yield.



Scheme 7. Arylation of 2-bromobenzyl alcohol by conventional heating.

Our entry into this field came through a desire to improve this reaction. Using microwave conditions (150 °C, 30 min), Ajaz²⁶ isolated 2-bromobenzyl benzene in 61 % yield. The reaction mixture was passed through a short column of silica gel using diethyl ether to elute the desired product. The crude product was determined by ¹H NMR analysis to require no further purification. The ease of this synthesis compared to that of the conventional thermal process prompted a study on optimal reaction conditions for a series of alcohols.

Project Goals

Building on previous work with benzyl alcohol substrates in Friedel-Crafts reactions, and known effects of catalysts on this reaction, we have attempted to improve upon this methodology by applying microwave irradiation. As a secondary goal we planned to develop a microwave electrophilic aromatic substitution reaction for use in undergraduate laboratories. Finally, the generality and simplicity of an alcohol plus arene coupling offers the opportunity for generation of chemical libraries.²⁷

Microwave Synthesis

Microwave-assisted organic reactions have been a topic of increasing interest during the past two decades. In 1986, Gedye and Giguere²⁸ noted that an increase in reaction rate was observed under microwave irradiation when compared to conventional heating methods. The mechanism for energy transfer in a microwave differs fundamentally from that of conventional heating techniques. With microwave radiation, energy is transferred directly to molecules through interaction with the electric field. As the electric field fluctuates, polar molecules and ionic species rotate to appropriately align with the field. Heat produced by dipole rotations or ionic conduction is transferred as thermal energy to the reaction mixture.²⁹ In conventional heating methods, the

transfer of thermal energy to a reaction mixture is dependent upon the thermal conductivity of the materials being penetrated, a comparatively slower process. Accelerated reaction times achieved in the microwave are often accompanied by improved yields and purity of products.^{28,29}

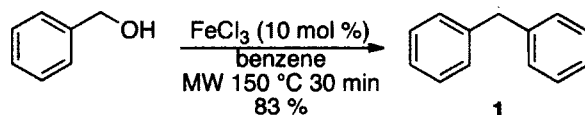
Many of the first microwave-assisted reactions were conducted in modified kitchen microwave ovens. Though microwave irradiation was pioneered in this way, technological advances provide for more sophisticated and higher power instruments that are designed for chemical synthesis. Present single mode reactors feature built-in magnetic stirrers, direct temperature control by infrared sensors, and software that enables real time temperature and pressure control to facilitate a variety of applications.^{29,30} These features, in concert with rapid heating and cooling, allow for an increase in control and reproducibility, which make microwave irradiation advantageous.

Results and Discussion

Initial Experiments

Building upon the initial arylation of 2-bromobenzyl alcohol by Ajaz using iron (III) chloride in the microwave, we began our investigation with benzyl alcohol using FeCl_3 as a catalyst. Support by comprehensive literature determined this species to be an excellent catalyst for Friedel-Crafts alkylations when using benzene. Iron (III) possesses additional *d*-orbitals relative to aluminum (III), which may provide an increase in polarizability of the catalyst. These *d*-orbitals weaken the Lewis acidity of FeCl_3 thus making it an ideal catalyst for arylation.

Preliminary reactions utilizing benzene as the solvent were successful (Scheme 8). The product mixture was passed through silica gel using diethyl ether to elute the desired product, diphenylmethane. Though obtained in good crude yield (83%), the ^1H NMR spectrum of the product showed minor resonances indicating several products; we looked to improve upon these conditions.



Scheme 8. Diphenylmethane synthesis.

We attempted to promote formation of the desired product by addition of co-solvents: dimethyl formamide, dichloromethane, *N*-methylpyrrolidinone or acetonitrile. These experiments led to complex product mixtures and confirmed that when using anhydrous iron (III) chloride, benzene is, unfortunately, the optimal solvent.

Due to low absorption of microwaves,²⁹ pure benzene heats slowly in a microwave reactor. A ramp time of 30 minutes is required to heat 4 mL of pure benzene to 150 °C. The polarized Lewis acid complex created in solution, presumably absorbs microwaves to heat the reaction mixture. In spite of limited solubility of anhydrous iron (III) chloride in benzene, when using 10 mol % of the catalyst (1 mmol alcohol substrate), 10-15 minutes is required to reach a temperature of 150 °C. Due to low solubility in benzene and long ramp times observed with anhydrous FeCl_3 we attempted to develop conditions using iron (III) hexahydrate. When a solution of 4 mL benzene and 10 mol % of the hexahydrate catalyst was subjected to microwaves, a temperature of 150 °C was reached in <10 minutes. Increased solubility of the catalyst allowed for a more efficient transfer of heat to the solution. This catalyst was further explored as a potential catalyst for microwave-assisted arylation of alcohols.

Anhydrous iron (III) chloride vs. iron (III) chloride hexahydrate

Because water is formed as a byproduct, the anhydrous iron (III) species may be deactivated. Also, oxidation by iron (III) chloride is facile. We reasoned that a weaker Lewis acid, such as iron (III) hexahydrate, may be more effective for alcohol substrates as well as water-promoted reactions. Iron (III) chloride hexahydrate (Figure 1, II) is stabilized by coordinated water, thus making it a weaker Lewis acid than its anhydrous form (I).

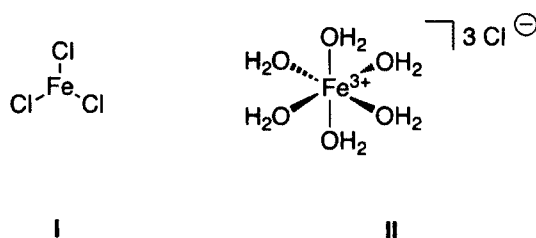
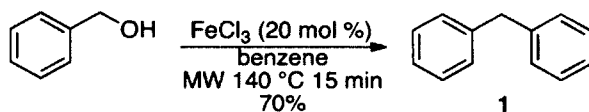


Figure 1. Iron (III) chloride species, anhydrous (I) and hexahydrate (II).

When using the hexahydrate iron (III) catalyst, sensitivity to water was no longer a limitation when considering solvents alternative to benzene. We briefly explored the potential for water promoted reactions when using $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$. Water is known to acquire properties, similar to organic solvents, at supercritical temperatures (approximately 375 °C). However, such temperatures could not be reached in the microwave reactor due to pressures exceeding 275 psi. Since we were unable to reach optimal temperatures for water-promoted reactions under these conditions, we conducted a second solvent study using co-solvents; dimethyl formamide, dichloromethane, *N*-methylpyrrolidinone, acetonitrile, benzene and 1,2-dichloroethane. As in the case of anhydrous iron (III) chloride, either starting material was recovered or complex reaction mixtures were observed due to interactions with solvent. Under various conditions we were unable to achieve the desired product in comparable yield and purity to reactions with the anhydrous iron (III) catalyst in benzene.

Optimization of Reaction Conditions

Ultimately, anhydrous iron (III) chloride and benzene was found to be the optimal catalyst and solvent for clean conversion to the desired products. As noted earlier, low solubility of the anhydrous catalyst in benzene caused poor absorption of microwaves; this resulted in long ramp times. In order to reach reaction temperatures more quickly we increased the molar equivalents of anhydrous FeCl_3 used in the reaction from 10 mol % to 20 mol %. We found that dilute conditions (1 mmol substrate: 4 mL benzene) were necessary to avoid secondary chemistry or self addition. In using 4 mL solvent, reaction mixtures were observed to consistently reach 140 °C in <5 mins for a variety of substrates. The efficiency of the title reaction using benzyl alcohol was checked using variable time studies. Following microwave irradiation (140 °C; 5, 15, 30 minutes), reaction mixtures were cooled to room temperature, chromatographed over silica gel, and eluted with hexane. Analysis of the filtrate by thin layer chromatography (10% EtOAc in hexane) and ^1H NMR indicated essentially complete conversion to products in 15 minutes (Scheme 9). Diphenylmethane (**1**) was isolated in 70% yield as a clear oil, requiring no further purification. Higher yields of the desired product were observed with a 30 minute reaction time (85% yield)



Scheme 9. Microwave-assisted benzylation of benzene.

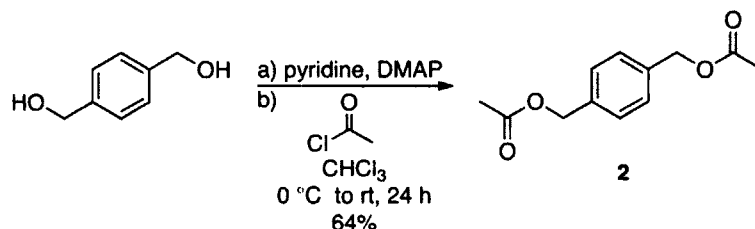
A series of benzylic alcohols (100 mg) was subjected to microwave irradiation at 140 °C in a solution of benzene (4 mL) with FeCl_3 (20 mol %). For all substrates complete conversion to products was observed within 30 minutes. Though previous experiments with benzyl alcohol suggest reduced reaction times in some cases,

products were shown to be essentially pure through analysis by ^1H and ^{13}C NMR spectroscopy (Appendix A).

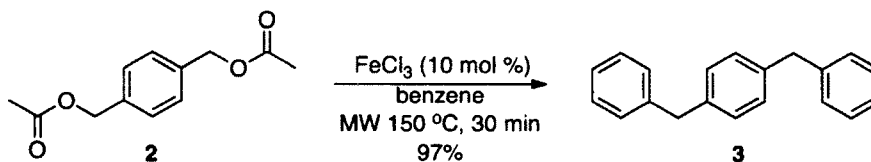
One disadvantage to these conditions was quickly observed to be solubility of some alcohol substrates in benzene. In the case of 1,4-bis(hydroxymethyl)benzene, poor solubility resulted in quantitative recovery of starting material.

Acetates as Substrates

The solubility of 1,4-bis(hydroxymethyl)benzene was increased by preparing the respective acetate using standard conditions (Scheme 10). The desired product (**2**) was obtained in 64 % yield as a white crystalline solid after an aqueous work up. The acetate substrate (**2**) was subjected to arylation conditions to afford (**3**) as colorless needles in 97 % yield (Scheme 11).



Scheme 10. Acylation of 1,4-bis(hydroxymethyl)benzene.



Scheme 11. Synthesis of 1,4-bis(phenylmethyl)benzene via diacetate.

The increased solubility of 1,4-bis(hydroxymethyl)benzene diacetate (**2**) in benzene compared to the alcohol precursor prompted the synthesis of a series of acyl derivatives. Acetates were synthesized from the corresponding alcohol using acetic anhydride or acetyl chloride under standard conditions (Scheme 11, Table 2).

Table 2. Acyl derivatives of respective alcohol substrates.

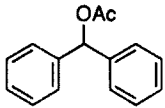
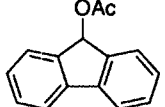
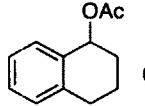
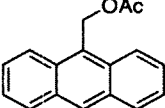
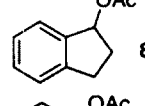
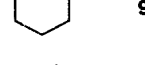
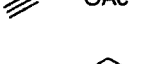

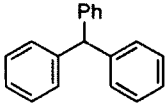
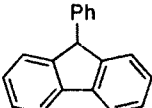
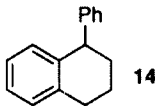
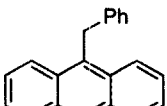
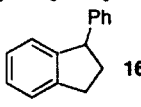


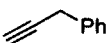

Entry	Product	% Yield
1	 4	84
2	 5	88
3	 6	88
4	 7	46
5	 8	95
6	 9	75
7	 10	25
8	 11	76

Table 3 shows an increase in reactivity for acetate analogs in several cases, possibly due to a more stabilized leaving group. Benzylic systems (Entries 1-5, Table 3) were found to be most efficient when compared to secondary and tertiary alcohol substrates (Entries 6 and 7).

Unfortunately, in the case of propargyl substrates, only starting material was recovered following microwave irradiation. However, based on the cationic pathway for this reaction and low stability of propargyl cations, this observation was not surprising. Future work with this methodology may include a more extensive study on solvent systems in order to stabilize such cations in solution to provide more efficient arylation.

Table 3. % Yield of acetate and alcohol substrates under optimized conditions.

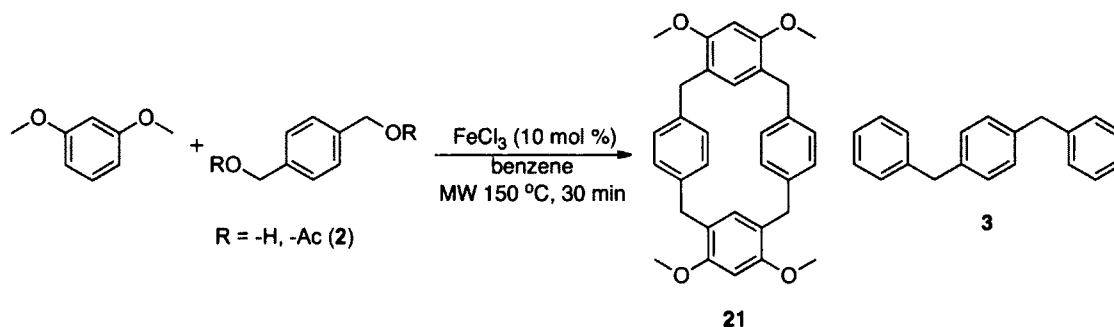
Entry	Product	% Yield	
		Alcohol	Acetate
1	 12	85	95
2	 13	68	65
3	 14	70	14
4	 15	48	29
5	 16	73	85
6	 17	5	28
7	 18	32	45
8	 19	SM	SM
9	 20	SM	SM

^a Optimized conditions (FeCl₃ (20 mol %), benzene, 140 °C, 30 minutes).

^b SM = starting material.

Applications Towards Cyclophane Synthesis

In efforts to expand the scope of this methodology we briefly explored the synthesis of cyclophanes. 1,3-Dimethoxybenzene provides an activated ring system for electrophilic aromatic substitution. We proposed bisalkylation using 1,4-benzenedimethanol, as well as the corresponding acetate (**2**), to afford the *meta-para*-substituted cyclophane (**21**, Scheme 12).



Scheme 12. Proposed synthesis of a *meta-para*-cyclophane.

Attempts to optimize conditions for this reaction with microwave irradiation yielded mostly **3** with no evidence for a product such as **21**. Though 1,3-dimethoxybenzene is substantially more reactive than benzene, dilute conditions using benzene as the solvent allowed for formation of 1,4-bis(phenylmethyl)benzene. An optimized procedure would be a facile way to obtain complex cyclophane products in high yield and purity, however we have not yet observed formation of the desired cyclophane.

Conclusions and Future Work

Microwave conditions have been developed for arylation of benzyl alcohols and acetates. Anhydrous iron (III) chloride is an inexpensive and widely available catalyst, that proved to be highly efficient in these reactions. Low catalyst loading and minimal use of benzene make this methodology desirable for the synthesis of many aryl compounds. Short reaction times and facile work up suggest this reaction may be useful for the generation of chemical libraries in which a series of alcohols or acetates are coupled to arenes.²⁷ We have yet to explore alternative arylating agents; future work will consist of studies including xylenes and toluene.

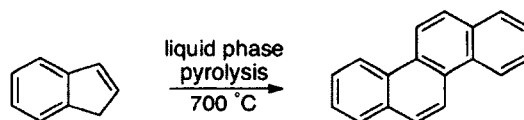
CHAPTER II

SOLUTION PHASE ROUTES TO *ORTHO*-XYLALLENE

Introduction

***ortho*-Xylylene: A Reactive and Versatile Intermediate**

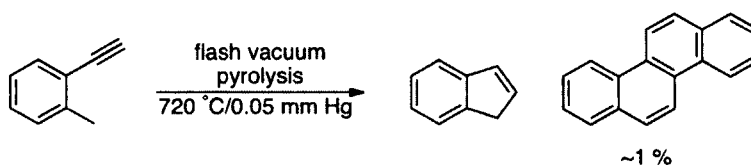
Highly reactive and non-isolable species such as *ortho*-xylylenes (1,2-quinodimethanes), have attracted the attention of both theoretical³¹ and synthetic³² chemists since their existence was initially proposed in 1910.³³⁻³⁶ The thermal interconversion between indene and isoindene has been well documented through numerous studies. Spilker³⁷ first reported the liquid phase pyrolysis of indene in 1893 (Scheme 13). The clean dimerization to afford chrysene was later applied by Badger and Spotswood^{38,39} to the synthesis of aromatic hydrocarbons. Their work confirmed efficient conversion to chrysene³⁸ with loss of hydrogen, as originally observed by Spilker.



Scheme 13. Pyrolysis of indene.

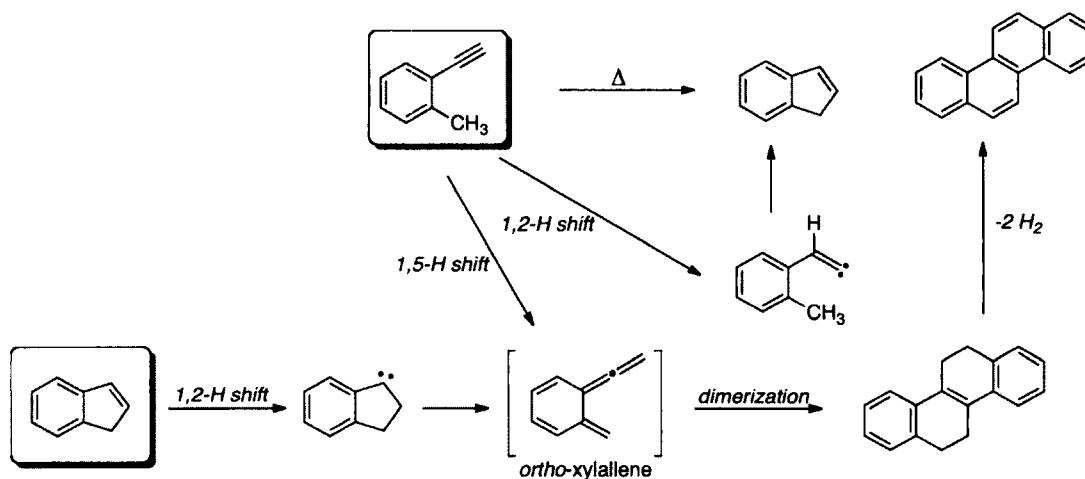
***ortho*-Xylallene**

Brown later studied *o*-ethynyl toluene in mechanistic studies involving the interconversion of indene at high temperatures. Pyrolysis of this substrate (Scheme 14) led to indene,⁴⁰ but Brown also noted chrysene as a minor product of the reaction. Brown proposed a hydrogen shift mechanism for rearrangement. He suggested that formation of chrysene was due to an allene intermediate, accessible from either indene or *o*-ethynyl toluene.



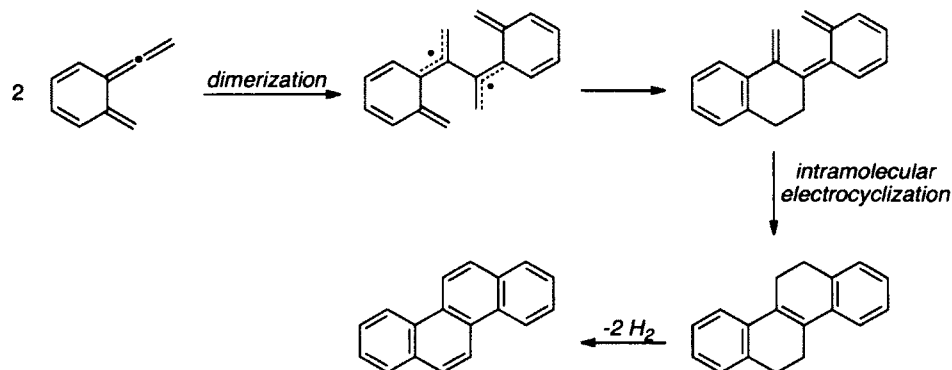
Scheme 14. Pyrolysis of *o*-ethynyl toluene.

The 1,2 and 1,5-hydrogen shift pathways proposed by Brown are outlined in Scheme 15. *ortho*-Ethynyltoluene may undergo a 1,2-hydrogen shift and subsequent carbene insertion to form indene. Based upon pyrolysis experiments, this pathway appears to dominate; a competitive 1,5-hydrogen shift to afford an allene intermediate is, however, also possible. This reactive intermediate may also be accessible from indene via 1,2-hydrogen shift and ring opening of the resultant carbene.



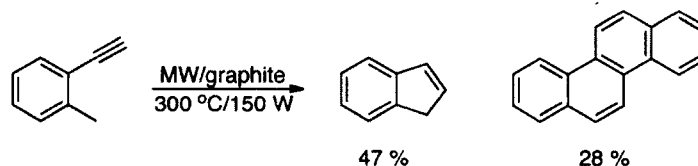
Scheme 15. Proposed routes to *ortho*-xylallene.

Brown suggested that formation of chrysene is due to the radical dimerization of the allene, for which the name *ortho*-xylallene seems appropriate. The bisallyl radical that is formed through dimerization may close in two steps (Scheme 16), a process analogous to that of traditional allenes. Further dehydrogenation of this dimer can then yield chrysene.



Scheme 16. Dimerization of *ortho*-xylallene to chrysene.

Our group has studied the reaction of *o*-ethynyl toluene by microwave flash pyrolysis (MFP). Ajaz²⁶ isolated a product mixture consisting primarily of indene (47%) and chrysene (28%) when *o*-ethynyl toluene was subjected to MFP conditions (Scheme 17).



Scheme 17. Microwave-flash pyrolysis (MFP) of *o*-ethynyl toluene.

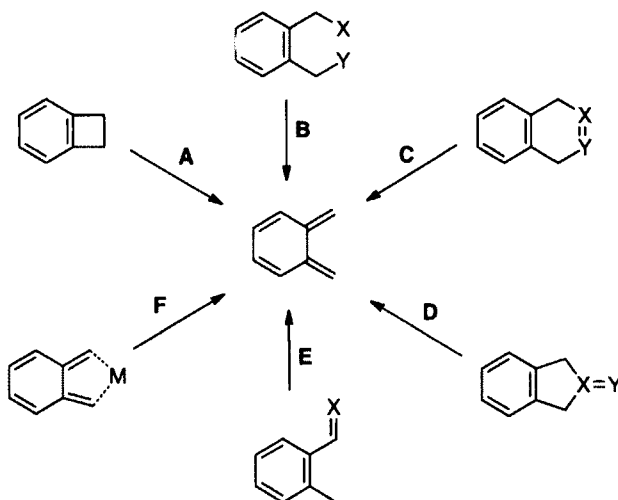
These results and the earlier report by Brown prompted a computational study on the dimerization of *ortho*-xylallene. Using density functional theory (DFT), Voukides⁴¹ concluded that a low barrier to dimerization (10.3 kcal/mol) shows this pathway to be more favorable than ring closure (34.3 kcal/mol) of this species. Furthermore, dimerization is driven by substantial predicted exothermicity. Though DFT calculations

support these experimental findings, no additional literature examples of *o*-xylallene intermediates could be located.

Current Routes to *o*-xyllylene

It may be possible to design solution-phase routes to *o*-xylallene based on chemistry of the well-known intermediate *o*-xyllylene. The chemistry of *o*-xyllylene has been summarized in several reviews.^{35,42} Applications in a variety of fields such as natural product synthesis, fullerene chemistry,^{43,44} and materials science have brought the development of these species to the forefront.

Scheme 18 shows the most common routes to *ortho*-xyllylenes. These include: thermolysis of benzocyclobutenes (path A),^{31,39,40,45,46} 1,4-elimination of α,α' -substituted *o*-xyllylenes (path B),⁴⁷⁻⁴⁹ reverse Diels-Alder reaction from benzo-fused heterocyclic compounds (path C and D),^{43,44,46,50,51} photorearrangement (path E),⁵² and from *o*-xyllylene-metal complexes (path F).⁵³



Scheme 18. The most efficient pathways for generation of *o*-quinodimethanes as classified by Segura and Martin.³⁵

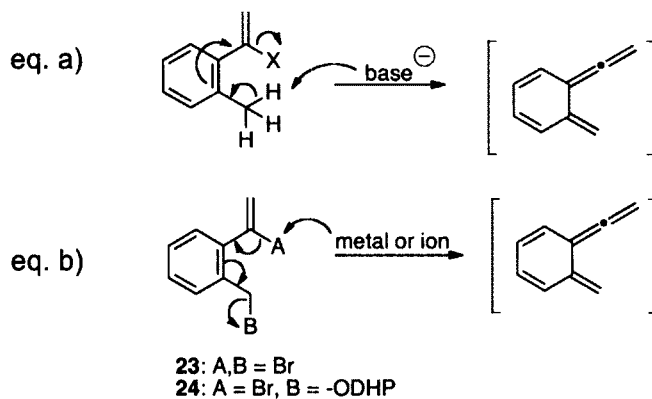
Project Goals

As described above, the chemistry of *o*-xylylene has been well investigated. There are currently no known solution phase routes to *o*-xylallene. It is our goal to develop such routes to these intermediates, with the expectation that this chemistry would find application in the synthesis of polycyclic aromatic compounds.

Results and Discussion

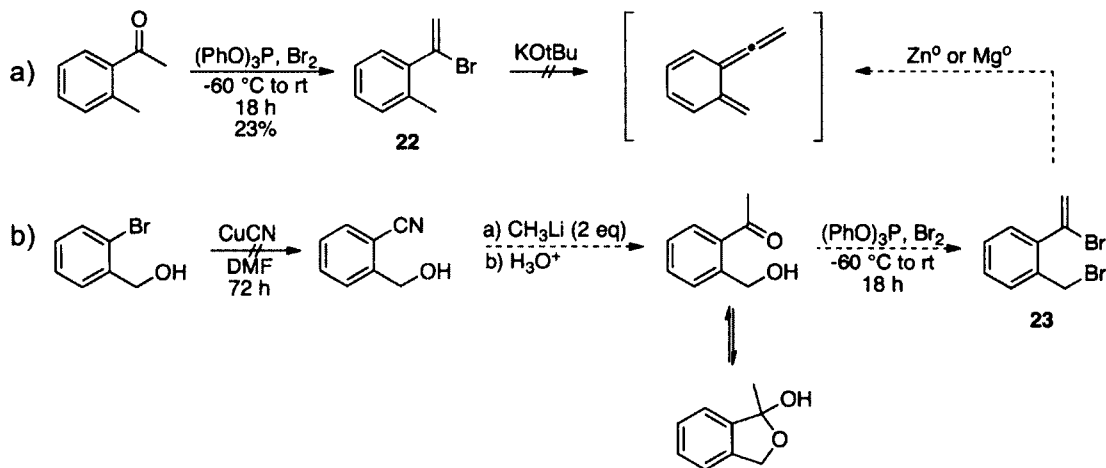
Attempted Routes to *ortho*-xylallene: 1,4-Elimination

Proposed routes to *o*-xylallene via 1,4 elimination are outlined in Scheme 19. This process may involve a) base-catalyzed eliminations or b) ion-catalyzed eliminations. By using potassium *tert*-butoxide we hoped to facilitate displacement of the halogen (X) (Scheme 19, eq. a). As shown in eq. b the substrate designed for ion catalyzed elimination would proceed in the reverse direction, though similarly leading to *ortho*-xylallene. The synthetic approach to several substrates designed for 1,4-elimination catalyzed by metals or ions is shown in Scheme 20. We attempted the synthesis of these starting materials to explore 1,4-elimination pathways to *o*-xylallene, however this proved to be unsuccessful.



Scheme 19. Routes to *ortho*-xylallene via (a) base induced or (b) metal or ion-catalyzed 1,4-elimination.

Vinyl-bromide **22** was prepared according to conditions developed by Spaggiari and coworkers.⁵⁴ After purification by flash chromatography, **22** was obtained as a yellow oil in 23% yield.



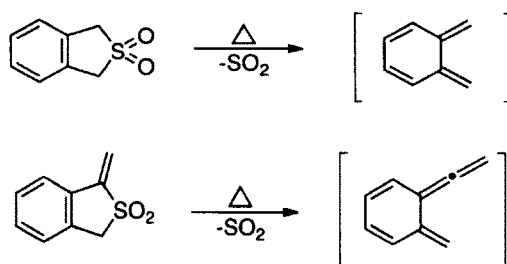
Scheme 20. Proposed synthesis by base-catalyzed (a) and ion-catalyzed (b) 1,4-elimination pathways.

However, when refluxed with potassium *tert*-butoxide in tetrahydrofuran formation of dehydrochrysene did not occur and starting material was recovered from the mixture (a, Scheme 20). The synthetic route involving the related vinyl dibromide also proved difficult (b, Scheme 20) due to a low yielding reaction of 2-cyanobenzyl

alcohol with CuCN. The starting alcohol was alternatively activated using 3,4-dihydropyran (**24**) however subsequent treatment with CuCN was again unsuccessful. Further work towards an ion-catalyzed route using a vinyl TMS was not pursued.

Cheletropic Extrusion of Sulfur Dioxide

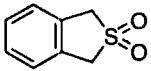

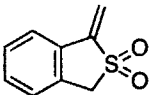
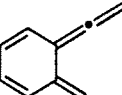
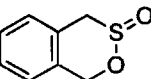

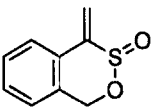
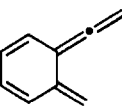
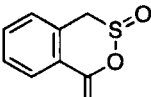
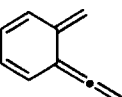
Thermal cheletropic elimination of sulfur dioxide has been observed experimentally by flash vacuum pyrolysis as an efficient route to *o*-xylene (Scheme 21). Based on known systems that afford the parent intermediate, we designed substrates that which could afford *ortho*-xylallene (Scheme 21).



Scheme 21. Formation of *ortho*-xylene and *ortho*-xylallene by thermal elimination of SO₂.

Prior to attempting increasingly complex synthetic routes to sulfone and sulfinate starting materials, we calculated the barrier for this process for a series of methylene analogs using density functional theory. The compounds known to yield *ortho*-xylene (Entries 1 and 3, Table 4) were found to have the lowest barriers to elimination. An increase of 5-10 kcal/mol was calculated for methylene derivatives (Entries 2, 4 and 5, Table 4). Barriers for formation of *o*-xylene (29.1-34.6 kcal/mol) are achieved at temperatures in excess of 700 °C via flash vacuum pyrolysis. The potential for analogous reactions to occur in solution with a barrier of 38.3-42.2 kcal/mol is therefore limited. We conclude that cheletropic extrusion of SO₂ is probably not a viable solution phase route to *ortho*-xylallene.

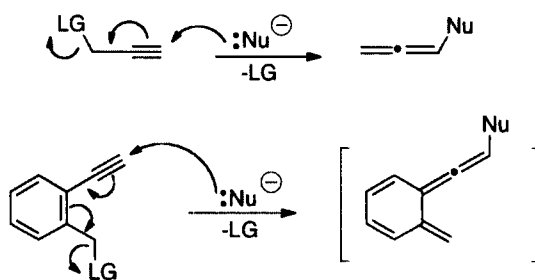
Table 4. Thermal elimination via cheletropic extrusion of sulfur dioxide.

Entry	Starting material	Barrier ^a (kcal/mol)	Product
1		34.6	
2		42.2	
3		29.1	
4		38.3	
5		42.2	

^a B3LYP/6-31g(d) energetics.

S_N2' Hydride Addition

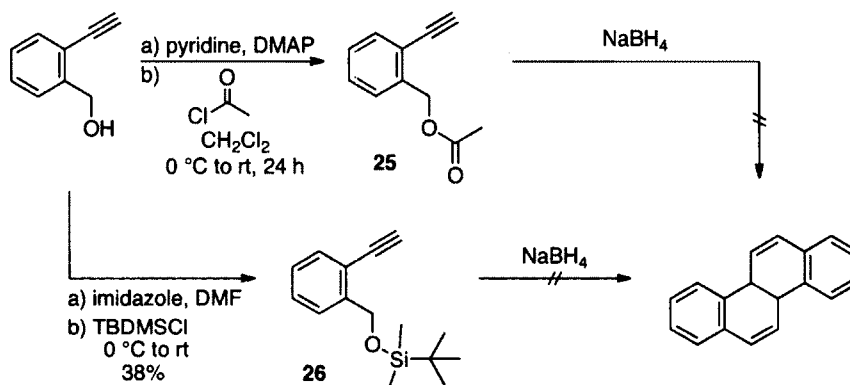
Conjugate addition/nucleophilic displacement in propargyl systems is a common route to allenes. We reasoned that a similar strategy might work for *ortho*-xylallene as shown in Scheme 22.



Scheme 22. Formation of *o*-xylallene via allene synthesis.

Several activating groups were used to enhance the leaving group ability of 2-ethynylbenzyl alcohol (Scheme 23). The substrate was first subjected to standard

conditions for acylation using acyl chloride. The product (**25**) was obtained in good yield as an oil and used without further purification.



Scheme 23. Activation of *o*-ethynylbenzyl alcohol and treatment with NaBH₄.

The Electron Transfer Model (ETM) was used to investigate the regioselectivity of *o*-ethynyl acetate (Cahill, K; Johnson, R. P., unpublished). Figure 2 shows localized spin density (in blue) of the radical anion at the terminal carbon of the alkyne (B3LYP/6-31+g(d)). This suggests nucleophilic addition would take place preferentially at this position. However, hydride addition via sodium borohydride was unsuccessful in a variety of solvents; methanol, tetrahydrofuran, and dioxane (Table 5).

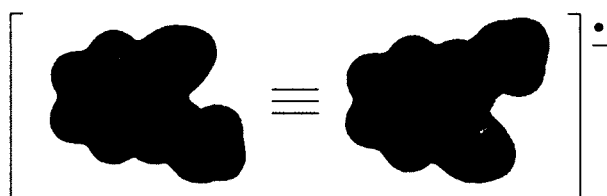


Figure 2 . Visualization of spin density on *o*-ethynylbenzyl acetate using ETM.

Table 5. Conditions attempted for *ortho*-xylallene using sodium borohydride.

Entry	Solvent	Temp °C	Time	Result
1	MeOH	25	1 h	-OH
2	THF	66	12 h	SM ^a
3	1,4-dioxane	101	12 h	SM, -OH, C=C

^a SM = starting material

When using sodium borohydride we observed cleavage of the acetyl group in methanol as well as in 1,4-dioxane. Though, reduction of the alkyne was also observed when using 1,4-dioxane. We determined that the acetate functionality would not be optimal and thus we attempted to activate the alcohol leaving group using TBDMS (**26**). However, the alkynyl starting material was recovered when subjected to sodium borohydride in methanol at reflux.

Conclusions and Future Work

Efforts towards a solution phase synthetic route to *ortho*-xylallene intermediates have so far proved unsuccessful. Our brief look at several different routes has narrowed the scope of potential pathways. We conclude 1,4-elimination and allene formation via S_N2' chemistry to be the most viable routes. Future work on this project should include focus on successful formation of starting materials such as **22** and **23** that may undergo 1,4-elimination. Similarly, the second pathway will require a more extensive look at leaving groups such as mesylates or tosylates. Furthermore, the use of nucleophiles that could provide stability to the allene may be beneficial.

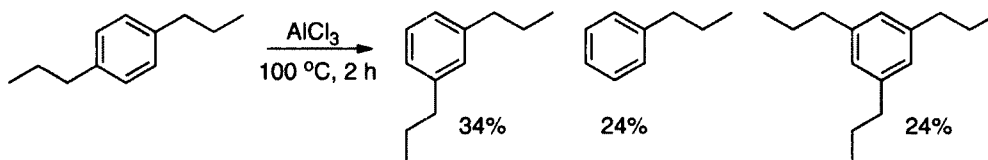
CHAPTER III

INTERCONVERSIONS OF SUBSTITUTED ARENES VIA *IPSO* ARENIUM IONS

Introduction

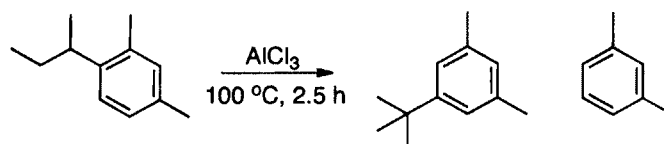
Substituent Migration in *Ipsso* Arenium Ions

Soon after the discovery of the Friedel-Crafts alkylation,¹ it was noted that *meta*-substituted products are often observed under strongly acidic conditions at elevated temperatures.⁵⁵⁻⁵⁷ In 1935 Baddeley and Kenner⁵⁷ explained these results by demonstrating that *p*-dipropylbenzene rearranged to *meta* products under Friedel-Crafts reaction conditions (Scheme 24). Norris and Rubinstein⁵⁸ reported similar rearrangements in a study of triethylbenzenes.



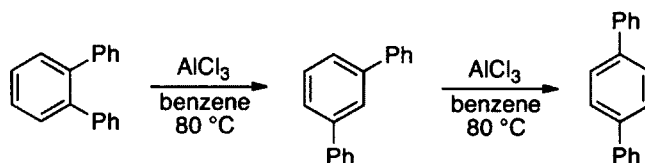
Scheme 24. Major formation of *meta*-substituted products reported by Baddeley and Kenner.

A few years later Nightingale^{56,59,60} concluded that a cationic mechanism for isomerization is likely, by demonstrating rearrangement of alkyl substituents. A product mixture largely containing 1,3-dimethyl-5-*tert*-butylbenzene and *meta*-xylene was recovered (Scheme 25) through treatment of 1,3-dimethyl-4-*sec*-butylbenzene with excess aluminum (III) chloride. Nightingale speculated that this result was due to increased stability of *meta*-isomers as a means to promote isomerization.



Scheme 25. The effect of aluminum (III) chloride on 1,3-dimethyl-4-butylbenzene.⁵⁹

In 1942 Allen and Pingert⁶¹ conducted a study of the treatment of *ortho*-terphenyl with excess aluminum (III) chloride in benzene. The authors reported sequential isomerization of *o*-terphenyl to the *meta* isomer and then on to *para* (Scheme 26). Based on these findings the *meta* isomer was presumed to be an intermediate in the isomerization of the *ortho* and *para* isomers.

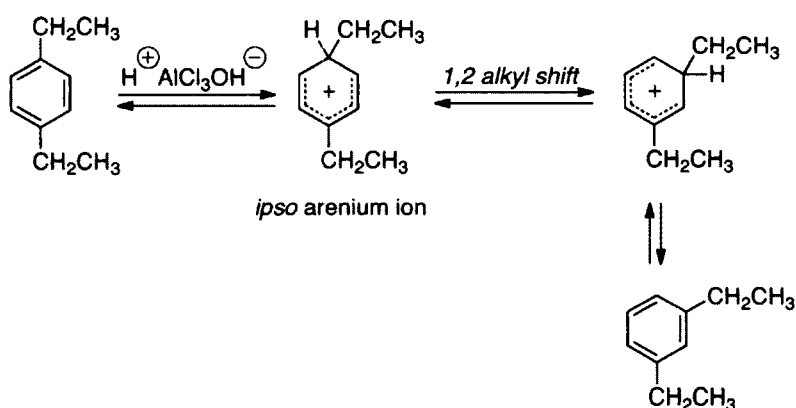


Scheme 26. Isomerization of *ortho*-terphenyl as shown by Allen and Pingert.⁶¹

It was also noted that under scrupulously anhydrous conditions, isomerization was not observed. Trace water is clearly needed to catalyze the reaction through reaction with AlCl_3 . Allen and Pingert could not provide explanation for this observation. A more comprehensive explanation for these complex rearrangements did not come until 20 years later.

Understanding the Mechanism for Rearrangement

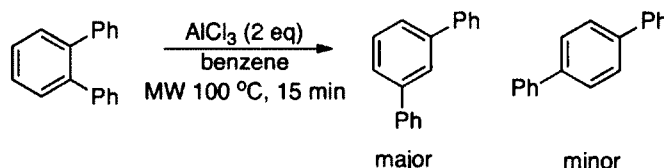
Olah and Meyer investigated the isomerization of terphenyls with water-promoted aluminum chloride in 1962.⁶² They concluded that a 1,2-phenyl migration would afford rearrangement. When starting from the *ortho* isomer they observed formation of *para* only after significant formation of *meta*-terphenyl, similar to Allen and Pingert. A later study of diethylbenzenes with water-promoted aluminum chloride provided additional mechanistic details. Olah proposed that an AlCl_3 -hydrate could protonate the arene (Scheme 27).⁶³ A series of subsequent 1,2-hydrogen shifts would provide an *ipso*-protonated species, with the potential to undergo alkyl migration. He concluded that this cationic mechanism, which involves a sequence of 1,2-shifts, would best explain the observed product distribution. As shown earlier by Allen and Pingert as well as Olah and Meyer, this mechanism involves a *meta*-intermediate. Without formation of the *meta*-substituted *ipso*-cation, isomerization by 1,2 alkyl-shift to *ortho* and *para* cannot occur. Olah later suggested that the major species in equilibrium should be the lowest energy cation formed in this process. Olah suggested increased stability of *meta*-type cations, similar to Nightingale.⁶⁴



Scheme 27. Proposed mechanism for the acid-catalyzed rearrangement of 1,4-diethylbenzene.⁶³

An Old Rearrangement of Terphenyl Rediscovered

The present study was prompted by a chance observation. When *ortho*-terphenyl was treated with excess aluminum chloride in the microwave at 100 °C for 15 minutes, Ajaz did not observe the desired cycloaromatized product, triphenylene, (Scheme 28). *meta*-Terphenyl was unexpectedly found to be the major product along with small amounts of the *para* isomer (Ajaz, A., unpublished). A literature search uncovered Allen and Pingert's report on terphenyl rearrangements, as well as abundant literature throughout the 1970's. We chose to carry out a systematic study of the terphenyl rearrangement.



Scheme 28. Product mixture recovered from attempted Scholl reaction.

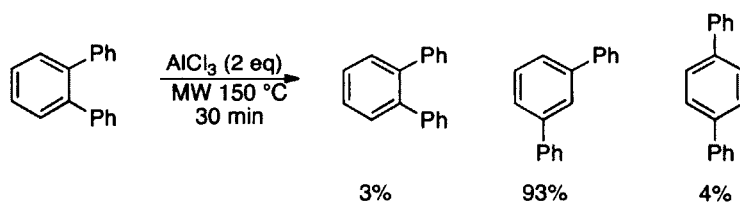
Goals of the Present Research

In spite of abundant early history, the rearrangement of substituted arenes through *ipso* arenium ions remains little known and poorly understood. Conditions must be established to monitor this rearrangement at different temperatures. A look at more complex rearrangements could shed light on many aspects of this mechanism. Also, microwave radiation has not yet been applied in the study of high temperature carbocations. Our goal in this thesis is to understand the mechanistic details and demonstrate the synthetic potential of this cationic rearrangement.

Results and Discussion

Establishment of an Acid Catalyzed Isomerization

The most obvious question we began with was what catalyzes these rearrangements? Similar rearrangements have been reported under strongly acidic conditions, including the reagents AlBr_3 , HBr , HCl , HF-BF_3 , H_2SO_4 , trifluoroacetic acid, and trifluoromethanesulfonic acid. Attempts to achieve equilibrium under these conditions are reported in the literature using the xylenes.^{55,65,66} We began with the initial conditions under which this isomerization was observed, using excess anhydrous aluminum (III) chloride and benzene (Scheme 29).



Scheme 29. Isomerization to *meta*-terphenyl via treatment with excess AlCl_3 .

meta-Terphenyl was the major constituent in the product mixture along with smaller amounts of the *ortho* and *para* isomers. However, results were not easily reproducible. We noted that trace water was necessary to promote the reaction when under rigorously anhydrous conditions no rearrangement was observed. Attempts to optimize the amount of water by addition of trace amounts (1 and 10 μL) were unsuccessful, as isomerization did not occur. The apparent role of water in these reactions rules out AlCl_3 as the catalyst. Due to inconsistent results with aluminum (III) chloride, we aimed to optimize alternate conditions to observe this isomerization.

Table 6 shows a variety of conditions that were explored to catalyze the rearrangement. In some cases competitive group-transfer chemistry was promoted over

isomerization. Analysis by gas chromatography was challenging, with complex reaction mixtures containing products unrelated to isomerization. In other cases, minimal reaction was observed. As noted in Table 6, rearrangement was observed with aluminum (III) chloride on sodium chloride. Though salt may have applications as a solid phase medium for microwave reactions, in this case isomerization was accompanied by inconsistent rapid increases in temperature and pressure.

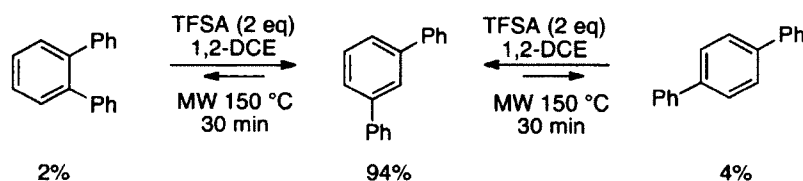
Table 6. Various conditions attempted to optimize isomerization.

Entry	Catalyst	Equivalents	Solvent ^a	Result
1	AlCl ₃	0.1	CH ₃ NO ₂	SM ^b
2	FeCl ₃	0.1	CF ₃ Ph	byproducts
3	AlCl ₃	1	NaCl	rearrangement/ poor temp control
4	HBF ₄	1	1,2-DCE	byproducts
5	BH ₃	1	THF	SM
6	BF ₃ •Et ₂ O	1	1,2-DCE	SM
7	I ₂	0.2	PhH	SM
8	TFA	0.1	1,2-DCE	SM
9	TFSA	1	1,2-DCE	rearrangement

^a 3-5 mL solvent was used depending on solubility of ~100 mg *o*-terphenyl.

^b SM = starting material.

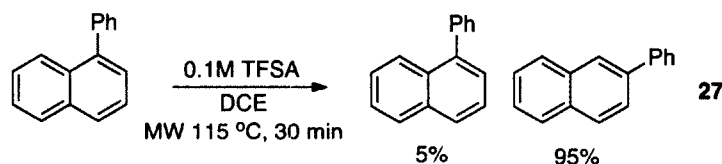
Moving to more extreme reaction conditions, *ortho*-terphenyl was treated with trifluoromethanesulfonic acid in 1,2-dichloroethane, reported conditions for studying activities of superacids.⁶⁷ Comparable results were observed under these conditions as with excess AlCl₃ in benzene at elevated temperatures (Scheme 30). The results unambiguously confirm a cationic mechanism which proceeds through protonation of the arene, as postulated by Olah.



Scheme 30. Analogous results achieved with AlCl₃ and TFSA in microwave.

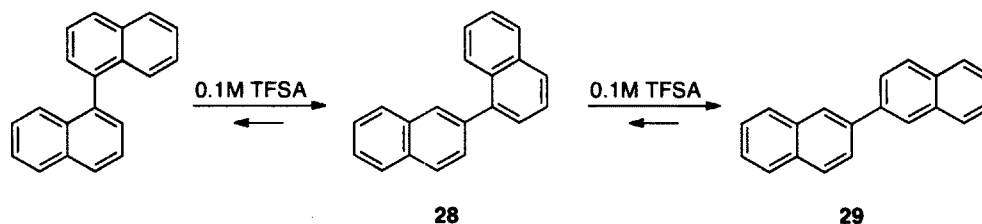
Microwave-Assisted Rearrangements

Related systems 1-phenylnaphthalene and 1,1'-binaphthalene were explored for similar rearrangements. When subjected to the optimized conditions for rearrangement 1-phenylnaphthalene was observed to rearrange to approximately 95% of the 2-isomer **27** (Scheme 31).



Scheme 31. Rearrangement of 1-phenylnaphthalene with TFSA in the microwave (% composition determined by capillary GC and ^1H NMR analysis).

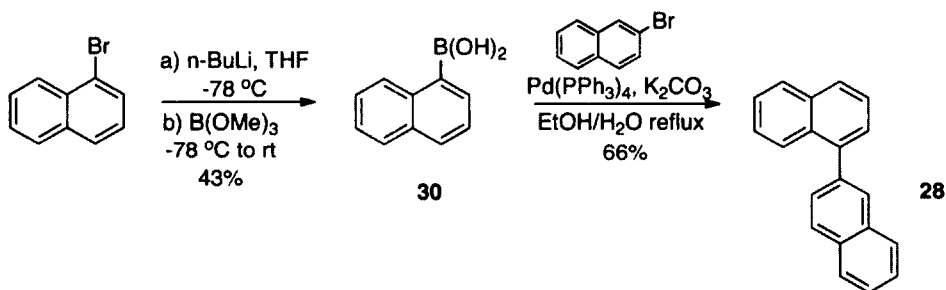
More surprisingly, 1,1'-binaphthalene was found to isomerize entirely to the 2,2'-isomer (**29**) under analogous conditions (Scheme 32). Similar to the terphenyl system, a 1,2'-binaphthalene species (**28**) was proposed to be an intermediate in this isomerization.



Scheme 32. Rearrangement of 1,1'-binaphthalene to 2,2'-binaphthalene.

Authentic samples of 1,2'-binaphthalene (**28**) and 2,2'-binaphthalene (**29**) were prepared by a Suzuki reaction. Scheme 33 shows the route taken for **28** where 1-bromonaphthalene was treated with *n*-BuLi in THF, to form boronic acid **30**, which precipitated from the solution as a white solid. The crude product was washed with hexanes and dried on a high vacuum pump. By melting point analysis (m.p 193 °C *lit.* 208-214 °C) the material was sufficiently pure to be carried on in the coupling reaction

with 2-bromonaphthalene. 1,2'-Binaphthyl (**28**) was obtained as a white solid (66 % yield) after column chromatography. Similarly, 2,2'-binaphthalene (**29**) was obtained using commercially available 2-bromonaphthalene and the corresponding boronic acid. A crystalline white solid was obtained (86 % yield) after further purification by column chromatography.



Scheme 33. Synthesis of 1,2'-binaphthalene (**28**).

When 1,1'-binaphthalene was treated with 0.1M TFSA in the microwave at 115 °C for 30 minutes, we were able to observe the intermediacy of 1,2'-binaphthalene (Figure 3) using capillary gas chromatography.

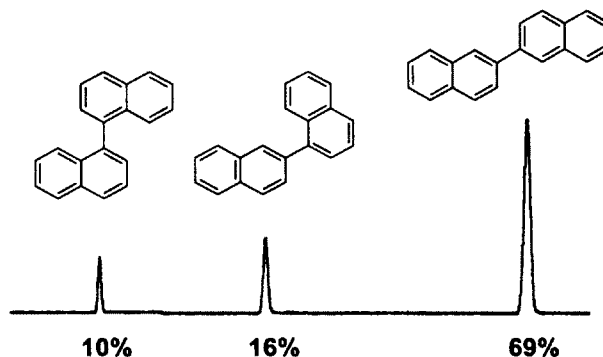
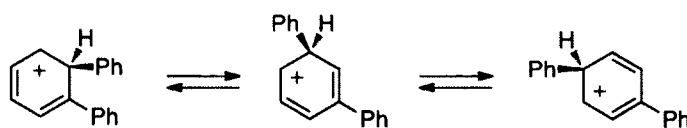


Figure 3. GC trace of 1,1'-binaphthyl treated with 0.1M TFSA (MW 115 °C, 30 min) (Column: JW Scientific DB-3 Temp: 250 °C)

Reaction Mechanism and Correlation with Computations

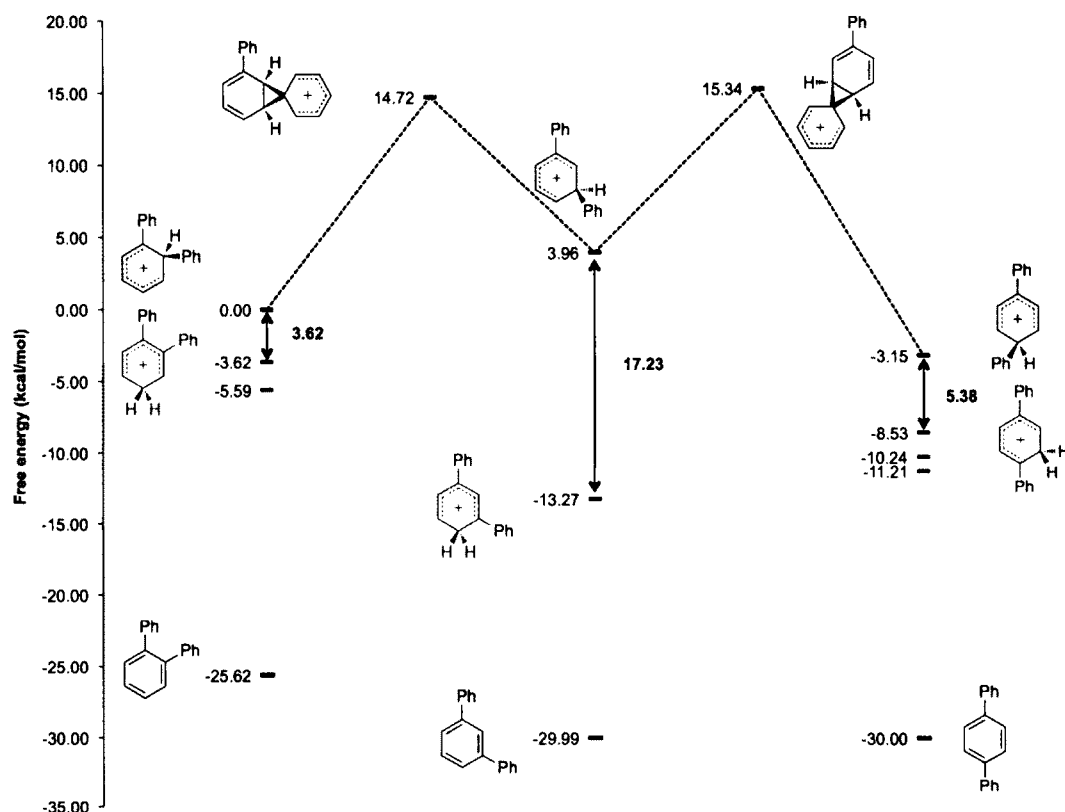
As a means to understand the product distribution of terphenyl isomers under highly acidic conditions, a complex potential surface was developed involving

carbocations and transition states. The free energy of all cations possible from the *ortho*, *meta*, and *para*-terphenyl isomers was calculated (Skraba, S., unpublished) using density functional theory (B3LYP/6-31+G(d,p)). This complex surface can be simplified by distinguishing cations that do and do not play a role in isomerization. Each terphenyl isomer can be protonated at multiple sites with facile interconversion expected by 1,2 hydrogen-shifts; these typically have barriers of 10-11 kcal/mol. Phenyl shifts may only occur from *ipso* protonated species as shown in Scheme 34.



Scheme 34. Terphenyl cations by which substituent migration can occur.

Skraba has calculated the relevant potential surface for terphenyl rearrangements. Scheme 35 summarizes free energies, with correction for solvation in dichloroethane with TfOH at ambient temperature. Based on the free energy of the neutral species, the product distribution observed at thermodynamic equilibrium would presumably contain approximately 50:50 *meta:para*-terphenyl (Scheme 35). Rearrangements must begin with protonation, shown here to be significantly endergonic in each case. Thus the concentration of carbocations should be low at any moment. Barriers for rearrangements among *ipso* carbocations are predicted to be modest. The *meta ipso* cation has the highest energy on the surface, but can easily rearrange to the lowest energy cation by 1,2 hydrogen-shift (4.76 kcal/mol) once reached.



Scheme 35. Energy surface for terphenyl rearrangement.

By starting from either *o* or *p*-terphenyl, the high-energy *meta ipso* cation is easily accessed to further rearrange. However, initial protonation of *meta* terphenyl would ultimately lead towards the lowest energy cation causing isomerization from *meta* terphenyl to be a much slower process relative to the other isomers. The lowest energy cationic form of the *meta* isomer is consistent with Olah's suggestion for a bias of *meta* isomers formed at equilibrium. Experiments conducted in the microwave reflect a rapid approach to this kinetic product distribution (94% *meta*-terphenyl). However, the lowest energy *meta* and *para* cations (shown in blue) differ by 4.74 kcal/mol and thus we would expect a product distribution containing more of the *para* isomer if the product distribution is dependent upon such species.

A similar computational analysis was conducted for the rearrangement of 1-phenylnaphthalene to 2-phenylnaphthalene as well as 1,1'-binaphthalene to 2,2'-binaphthalene (Appendix B). Product distributions achieved in the microwave accurately reflected a product distribution based on low energy cations as observed with the terphenyl system.

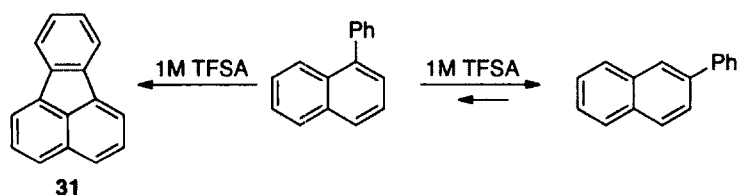
Optimization of Reaction Conditions: Higher Acid Concentrations

We attempted to monitor this rearrangement at room temperature based on low barriers calculated for migration in order to observe the product distribution at true equilibrium. *ortho*-Terphenyl was treated under various amounts of TFSA at room temperature (0.01M, 0.10M, and 1.1M). Over 3 days the 0.01 and 0.10M TFSA solutions remained unchanged. However, the 1.1M TFSA solution showed 70 % conversion to the *meta*-isomer. Further work concluded a 1.1M TFSA solution using 4 mL 1,2-dichloroethane and 100 mg of substrate to be efficient for isomerization. Rearrangement was shown to occur more quickly under reflux (84 °C).

Each terphenyl isomer was subjected to the optimized conditions (1.1M TFSA, 1,2-DCE, reflux) and monitored by capillary GC to observe the rearrangement over the course of 14 days. A product distribution of approximately ~0:65:35 *ortho:meta:para* was sustained by each reaction for 8 days before being quenched. The distribution at equilibrium reflects the energy of *meta* and *para* cations that are expected to bias this rearrangement. Likewise, it was expected that the rate at which each isomer approached equilibrium would vary between the isomers. This was observed as the *ortho* isomer rapidly converted to 97% of the *meta* isomer within the first hour; consistent with microwave experiments. The *para* isomer quickly converted to the *meta* isomer though at a slower rate than *ortho*-terphenyl. Our theory that the *meta* isomer would rearrange

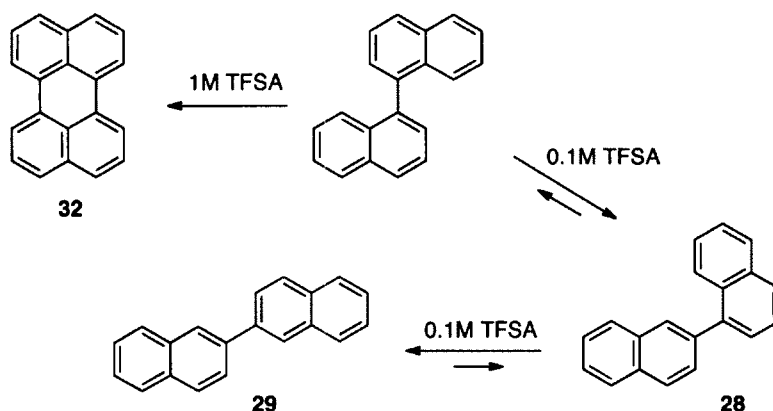
slowest was confirmed and further supports the mechanism we have proposed. Brown and Jungk⁶⁶ had made the same conclusion from their study of the xylenes in 1955.

When 1-phenylnaphthalene and 1,1'-binaphthalene were subjected to the optimized conditions for rearrangement (1.1M TFSA, 1,2-DCE, reflux) we discovered another carbocationic mechanism. Once equilibrium had been reached in either case, a new peak in the chromatogram began to form irreversibly from the product mixture. In the case of phenylnaphthalene, after 4 hours the reaction mixture contained 1-phenylnaphthalene (2%), 2-phenylnaphthalene (57%) and fluoranthene (41%). The reaction was prolonged for 7 days in order to observe any other types of product formation. The black resin that was then recovered was chromatographed over silica with hexane to afford naphthalene (57%), fluoranthene **30** (31%) and 2-phenylnaphthalene (12%) by capillary GC analysis.



Scheme 36. Formation of fluoranthene from 1-phenylnaphthalene.

Under analogous conditions 1,1'-binaphthalene proceeded irreversibly to perylene (**31**) within 30 minutes (100% conversion by capillary GC analysis) (Scheme 37). After 7 days, perylene was recovered (7%) as a yellow solid from the reaction mixture with trace formation of oligomers. At this time, our results simply show C-C bond formation under superacidic conditions. Based on these findings it will be necessary to conduct similar experiments on a shorter time scale as to increase the recovery of products.



Scheme 37. Formation of perylene from 1,1'-binaphthalene.

Cycloaromatized products such as fluoranthene and perylene are traditionally prepared using Scholl reaction⁶⁸ conditions. This well-known aryl-aryl coupling reaction has been shown to occur with excess Lewis acids such as FeCl_3 as well as AlCl_3 at elevated temperatures.⁶⁹ More recently various oxidants such as DDQ,⁷⁰ CuCl_2 and MoCl_5 have been incorporated to allow for more mild conditions, while increasing the rate of the reaction.⁶⁹ Though the coupling of arenes has been successful under these conditions, the mechanism for this reaction is widely debated. Our success in promoting Scholl chemistry using trifluoromethanesulfonic acid suggests a carbocationic mechanism in which an oxidant may be unnecessary. We are currently working to investigate this problem by computational chemistry. Initial experiments with related systems 9-phenylanthracene and 9,10-diphenylanthracene have shown similar C-C bond formation (Skraba, S., unpublished).

Conclusions and Future Work

Rearrangement of *ipso* arenium ions provides a simple mechanism for the interconversion of substituted benzene isomers. Interconversion of terphenyl isomers catalyzed by aluminum chloride was first reported by Allen and Pingert⁶¹ in 1942. We

have shown here that triflic acid in dichloroethane is an efficient medium for studying these rearrangements. Product distributions favor *meta* isomers, based on the relative energy of carbocations in solution. The product distributions observed after prolonged reaction times are consistent with theory. Similar rearrangements have been observed for the phenyl naphthalenes favoring the 2-isomer and 1,1'-binaphthyl which rearranges completely to the 2,2'-isomer. Future work based on the differing rates for isomerization will be important to understand the intricacies of this isomerization. The most recent results showing Scholl-type products will require a new look at the mechanism for this reaction. A computational analysis of carbocations that will play a role in this mechanism will dictate the development of reaction conditions. Based on barriers for C-C bond formation the use of microwave radiation may be advantageous for these reactions. Much additional work remains to establish the mechanistic details and synthetic applications of these fascinating rearrangements.

CHAPTER IV

EXPERIMENTAL

General Experimental Section

Solvents

Diethyl ether, dichloromethane (CH_2Cl_2), and benzene were purchased from EMD Serono Inc., or Pharmco-AAPER. Benzene was stored over 4Å molecular sieves prior to use. Anhydrous solvents, passed through drying agent with nitrogen pressure, were obtained from an Innovative Technology Inc. Solvent Delivery System prior to use. Diethyl ether and tetrahydrofuran (THF) obtained from the solvent delivery system were stored over 4Å sieves.

Reagents

All reagents were received from commercial sources and were used as received unless otherwise noted. Reagents were obtained from the following sources: Fisher Scientific (Acros), Alfa Aesar, TCI America, Sigma-Aldrich and Cambridge Isotope Laboratories.

Reactions

Glassware and magnetic stir bars were stored in an oven at 75 °C prior to use. Sigma-Aldrich Natural Rubber Septa and Teflon coated magnetic stir bars were utilized. Unless otherwise specified, nitrogen gas was introduced to the reaction vessel through a Tygon® tube with a needle or glass inlet adaptor. Henke Sass Wolf Norm-ject® plastic syringes and oven-dried Popper & Sons needles were used for volumetric addition of reagents unless otherwise noted.

Chromatography

Flash column chromatography was performed with Silicycle SiliaFlash® P60 Flash Silica Gel with 40-63 µm particle size. Preparative chromatography was accomplished through the use of Analtech Uniplat Silica Gel GF 1000 micron UV 254 glass-backed plates. Mobile phases were freshly prepared as described in the detailed experimental section. Thin Layer Chromatography (TLC) analysis was conducted using Whatman polyester-backed Silica Gel 60Å 250 µm thickness flexible plates with fluorescent indicator. TLC solvent systems were identical to the respective mobile phase used for column chromatography unless otherwise specified.

Instrumentation

Analysis by Nuclear Magnetic Resonance (NMR) spectroscopy was recorded on a Varian Mercury spectrometer operating at 400 MHz for ¹H and 100 MHz for ¹³C spectroscopy. All spectra were measured in deuteriochloroform (CDCl₃) purchased from Cambridge Isotope Laboratory and stored over 4Å sieves. All ¹H resonances were reported relative to an internal standard tetramethylsilane (TMS) (δ 0 ppm), unless otherwise noted. The following abbreviations were used to denote multiplicities: s = singlet, d = doublet, t = triplet, m = multiplet. Infrared (IR) spectroscopy was conducted

using a Thermo Nicolet iS10 FTIR with diamond ATR probe. Analytical gas chromatography was performed with an FID equipped Hewlett-Packard HP 6890 gas chromatograph with an Agilent JW Scientific DB-3 nonpolar column (30 m × 0.320 mm, -60 to 325/350 °C, 1.00 micron). Data analysis was recorded as product distribution ratios on a Hewlett-Packard HP 3395 integrator. Microwave-assisted reactions were conducted in a CEM Discover single-mode microwave reactor using a sealed reaction vessel.

Detailed Experimental Section

Chapter I

General Procedure for Microwave-assisted EAS

All experiments were carried out in a CEM Discover microwave reactor using a sealed tube method in Pyrex® vials with snap-on Teflon® caps. Dynamic power mode was utilized to ensure controlled rapid heating of the sample. Typical microwave operating parameters were 140 °C hold temperature, 300 W maximum power, and 30 minute run time. The crude reaction mixture was filtered over a short column of silica gel (ca. 2 cm) and eluted with distilled hexanes to isolate products. Experiments were monitored closely for excessive rise in pressure.

1,4-bis(hydroxymethyl)benzene diacetate (2)

The following procedure was adapted from Wang and Zhang.⁷¹ An oven-dried 100 mL round bottom flask was equipped with stir bar and rubber septum. The flask was flushed with nitrogen before 1,4-benzenedimethanol (1.0 g, 7.2 mmol) was dissolved in CHCl₃ and charged to the flask. DMAP (92 mg, 7.2 mmol) was then quickly added by removing

the septum, followed by pyridine (1.4 mL, 17 mmol). The solution was cooled to 0 °C using an ice water bath before slowly adding acetyl chloride (3.6 mL, 51 mmol) via syringe. After 30 minutes, the reaction was warmed to room temperature and stirred for 12 hours under nitrogen. The reaction mixture was quenched with 1M HCl (50 mL) and transferred to a separatory funnel. The organic layer was washed with water (5 × 100 mL) and brine (50 mL). The organic layer was then dried over magnesium sulfate and concentrated under reduced pressure (*ca.* 9 Torr) to afford a white crystalline solid (m.p. 44-47 °C *lit.* 48-49 °C) (0.85 g, 64%). ¹H NMR (400 MHz, CDCl₃) δ 7.36 (s, 4H), 5.10 (s, 4H), 2.10 (s, 6H). ¹³C NMR (101 MHz, CDCl₃) δ 171.02, 128.68, 66.11, 21.21

1,4-bis(phenylmethyl)benzene (3)

An oven-dried 10 mL vial was equipped with a stir bar, septum and N₂ inlet. 1,4-bis(acetoxymethyl) benzene (0.31 g, 1.3 mmol) was added, followed by anhydrous FeCl₃ (48 mg, 0.01 mmol). Benzene (5 mL) was charged to the flask before the vessel was purged, capped and placed in the microwave reactor for 30 minutes (130 °C, 300 W). The reaction mixture was cooled to room temperature and passed through a short column of silica, using diethyl ether to elute the product. The filtrate was concentrated by rotary evaporation to afford (3) as a white crystalline solid requiring no further purification (m.p 77-79 °C *lit.* 85-86 °C) (0.34 g, 97%). ¹H NMR (400 MHz, CDCl₃) δ 7.24-7.17 (m, 10H), 7.09 (s, 4H), 3.92 (s, 4H). ¹³C NMR (101 MHz, CDCl₃) δ 141.49, 139.14, 129.28, 129.21, 128.73, 126.32, 41.84.

1-acetoxy-1,1-diphenyl-methane (4)

The standard conditions used for acylation were applied to the synthesis of 4. Once the organic layer was concentrated to a yellow oil it was filtered over a short path of silica gel. Product was eluted using distilled hexanes. The filtrate was concentrated by rotary

evaporation to afford **4** as a clear liquid (1.0 g, 67%). ^1H NMR (400 MHz, CDCl_3) δ 7.35-7.28 (m, 8H), 7.26 (t, 1H), 7.22 (t, 1H), 6.88 (s, 1H), 2.11 (s, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ 170.26, 140.53, 128.81, 128.21, 127.40, 77.16, 21.56.

9-acetoxyfluorene (5)

The crude solid was dissolved in distilled hexanes and passed over a silica gel pad. Title compound (**5**) was isolated as a clear crystalline solid by concentration of the filtrate under reduced pressure (m.p. 68-70 °C, *lit.* 70-72 °C) (1.1 g, 88%). ^1H NMR (400 MHz, CDCl_3) δ 7.65 (d, 2H), 7.54 (d, 2H), 7.40 (t, 2H), 7.29 (t, 2H), 6.80 (s, 1H), 2.19 (s, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ 172.02, 142.25, 141.25, 129.73, 128.09, 126.13, 120.27, 75.38, 21.51.

1,2,3,4-tetrahydro-naphthalen-1-yl acetate (6)

The crude product was chromatographed on a short column of silica using hexanes to afford **6** as a clear liquid (0.86 g, 88%). ^1H NMR (400 MHz, CDCl_3) δ 7.27 (d, 1H), 7.22 (dd, 1H), 7.18 (dd, 1H), 7.12 (d, 1H), 6.00 (s, 1H), 2.90-2.70 (m, 2H), 2.08 (s, 3H), 2.02-1.92 (m, 3H), 1.87-1.78 (1H). ^{13}C NMR (101 MHz, CDCl_3) δ 171.02, 138.17, 134.77, 129.68, 129.32, 128.32, 126.31, 70.21, 29.31, 29.21, 21.75, 19.03.

9-acetoxyanthracene (7)

The crude product was isolated as yellow needles requiring no further purification (m.p. 109-111 °C, *lit.* 108-110 °C) (1.0 g, 67% yield). ^1H NMR (400 MHz, CDCl_3) δ 8.51 (s, 1H), 8.32 (d, 2H), 8.04 (d, 2H), 7.58 (td, 2H), 7.51 (td, 2H), 6.15 (s, 2H), 2.08 (s, 2H). ^{13}C NMR (101 MHz, CDCl_3) δ 171.54, 131.61, 131.61, 131.26, 131.26, 129.43, 129.35, 126.89, 126.41, 125.34, 124.14, 59.05, 21.27. ^{13}C NMR (101 MHz, CDCl_3) δ 171.54,

131.61, 131.61, 131.26, 131.26, 129.43, 129.35, 126.89, 126.41, 125.34, 124.14, 59.05, 21.27.

1-indanylacetate (8)

Crude product was passed through a short silica column using hexanes to afford 1-indanylacetate (**8**) as a clear liquid (1.2 g, 95%). ^1H NMR (400 MHz, CDCl_3) δ 7.41 (d, 1H), 7.32-7.26 (m, 2H), 7.24-7.19 (m, 1H), 6.19 (dd, 1H), 3.09 (m, 1H), 2.88 (m, 1H), 2.51 (m, 1H), 2.10 (m, 1H), 2.06 (s, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ 171.33, 144.65, 141.28, 129.18, 126.93, 125.78, 125.04, 121.11, 32.53, 30.44, 21.58.

cyclohexyl acetate (9)

The crude material obtained from standard conditons was chromatographed on a short silica column using hexanes to afford **9** as a clear liquid (1.1 g, 75%). ^1H NMR (400 MHz, CDCl_3) δ 4.74 (m, 1H), 2.03 (s, 3H), 1.85 (m, 2H), 1.72 (m, 2H), 1.54 (m, 4H), 1.25 (m, 1H). ^{13}C NMR (101 MHz, CDCl_3) δ 170.84, 72.89, 31.85, 25.57, 24.01, 21.65.

2-propynyl acetate (10)

Title compound **10** was isolated as a light yellow oil (83 mg, 25%). ^1H NMR was consistent with reported spectral data in literature.⁷² ^1H NMR (400 MHz, CDCl_3) δ 4.68 (d, 2H), 2.53 (t, 1H), 2.11 (s, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ 170.3, 77.8, 75.1, 20.9.

2-butyn-1,4-diol diacetate (11)

Standard conditions were applied to the synthesis of 2-butyn-1,4-diacetate (**11**). The desired product was obtained as a pale yellow liquid (3.0 g, 76%). ^1H NMR (400 MHz, CDCl_3) δ 4.72 (s, 4H), 2.11 (s, 6H). ^{13}C NMR (101 MHz, CDCl_3) δ 170.38, 80.94, 52.29, 20.91.

triphenylmethane (12)

Compound **12** was obtained using optimized conditions for arylation using anhydrous FeCl_3 and benzene. Product was obtained as a white solid (m.p. 85-88 °C, *lit.* 90-94 °C). ^1H NMR (400 MHz, CDCl_3) δ 7.28 (t, 6H), 7.20 (t, 3H), 7.12 (d, 6H), 5.55 (s, 1H). ^{13}C NMR (101 MHz, CDCl_3) δ 144.15, 129.72, 128.56, 126.56, 57.10.

9-phenylfluorene (13)

When the corresponding alcohol or acetate was subjected to optimized conditions for arylation **13** was isolated as a white solid. Spectral data was consistent with data reported by Vougioukalakis.⁷³ ^1H NMR (500 MHz, CDCl_3) δ 7.84 (d, 2H), 7.42 (t, 2H), 7.32 (m, 7H), 7.13 (d, 2H), 5.09 (s, 1H). ^{13}C NMR (125 MHz, CDCl_3) δ 147.90, 141.60, 141.01, 128.68, 128.34, 127.30, 126.83, 125.33, 119.87, 54.44.

1,2,3,4-tetrahydro-1-phenylnaphthalene (14)

Compound **14** was isolated as a white crystalline solid by following the procedure described for arylation. ^1H NMR and ^{13}C NMR were consistent with data reported in the literature.⁷⁴ ^1H NMR (300 MHz, CDCl_3) δ 7.30-7.00 (m, 8H), 6.84 (d, 1H), 4.12 (t, 1H), 2.92-2.81 (m, 2H), 2.21-2.12 (m, 2H), 1.93-1.70 (m, 3H). ^{13}C NMR (300 MHz, CDCl_3) δ 147.40, 139.40, 137.60, 130.20, 128.90, 128.80, 128.20, 125.90, 125.60, 45.60, 33.30, 29.80, 21.00.

9-(phenylmethyl)-anthracene (15)

Compound **15** was prepared using the general procedure for arylation. The product was isolated as a light yellow solid and spectral data was found to be consistent with literature.⁷⁵ ^1H NMR (400 MHz, CDCl_3) δ 5.01 (s, 2H), 7.10-7.19 (m, 5H), 7.44-7.47 (m, 4H), 8.02 (m, 2H), 8.21(m, 2H), 8.43 (m, 1H).

1-phenylindane (16)

Compound **16** was isolated as a light yellow oil. Analysis by ^1H and ^{13}C NMR compared to spectral data reported by Deng.⁷⁶ ^1H NMR (500 MHz, CDCl_3) δ 7.40-7.37 (m, 3H), 7.32-7.25 (m, 4H), 7.20 (t, 1H), 7.04 (dd, 1H), 4.42 (t, 1H), 3.16-3.11 (m, 1H), 3.07-3.00 (m, 1H), 2.70-2.63 (m, 1H), 2.19-2.11 (m, 1H). ^{13}C NMR (125 MHz, CDCl_3) δ 147.20, 145.70, 144.60, 128.80, 128.40, 126.90, 126.70, 126.60, 125.20, 124.70, 52.00, 36.90, 32.20.

Chapter II

1-(1-bromoethenyl)-2-methyl benzene (22)

The synthesis of the following vinyl halide was obtained from Spaggiari *et al.*⁵⁴ An oven-dried 250 mL round bottom flask was equipped with a magnetic stir bar, rubber septum and nitrogen line inlet. CH_2Cl_2 (100 mL) was charged to the flask followed by triphenyl phosphite (11 mL, 4.1 mmol). The solution was cooled to $-60\text{ }^\circ\text{C}$ using dry ice-chloroform. Bromine (2.3 mL, 4.5 mmol) was added via syringe, followed by triethylamine (6.8 mL, 4.8 mmol) and 2-methylacetophenone (4.8 mL, 3.7 mmol). The reaction mixture was allowed to warm to ambient temperature and was stirred for 1 hour. The solution became dark red overnight and after 24 hours, reflux was started. Subsequent to a 24 hour reflux, the solution was cooled to r.t and transferred to a separatory funnel with CH_2Cl_2 (50 mL). The organic layer was washed with saturated sodium bisulfite (50 mL), water ($3 \times 100\text{ mL}$) and brine (100 mL). The organic layer was dried over sodium sulfate and concentrated by rotary evaporation to afford title compound **22** as a crude brown oil. This was purified by column chromatography using

hexanes to afford pure 1-(1-bromoethenyl)-2-methyl benzene as a yellow oil (1.7 g, 23 %). ^1H NMR (400 MHz, CDCl_3) δ 7.25 (m, 1H), 7.24-7.13 (m, 3H), 5.80 (dd, 2H), 2.39 (s, 3H). ^{13}C NMR (101 MHz, CDCl_3) δ 140.51, 135.81, 130.54, 129.50, 129.13, 129.09, 125.94, 121.11, 20.00.

2-(2-bromophenylmethoxy)tetrahydro-[2H]pyran (24)

An oven-dried 250 mL round bottom flask was equipped with a magnetic stir bar and rubber septum with nitrogen inlet. 2-Bromobenzyl alcohol (3.0 g, 16 mmol) was dissolved in CH_2Cl_2 (10 mL) and transferred to the flask via syringe. The solution was diluted with CH_2Cl_2 (50 mL) and cooled to 0 °C with an ice water bath. Dihydropyran (6.8 mL, 80 mmol) was charged to the flask. The septum was then briefly removed to add *p*-toluenesulfonic acid (0.31 g, 1.6 mmol) as a solid. The reaction was warmed to r.t and stirred overnight with a nitrogen balloon. Sat. sodium bicarbonate (20 mL) was added to the flask and stirred. The aqueous layer was decanted and brine (20 mL) was then added to the flask. The organic layer was removed and dried over sodium sulfate. After concentration by rotary evaporation (ca. 16 Torr), the resultant brown-red liquid was purified by column chromatography with 5% EtOAc in hexanes to afford **24** as a colorless oil (2.2 g, 50%). ^1H NMR (400 MHz, CDCl_3) δ 7.53 (t, 2H), 7.32 (t, 1H), 7.14 (t, 1H), 4.83 (d, 1H), 4.78 (t, 1H), 4.57 (d, 1H), 3.93 (t, 1H), 3.59 (m, 1H), 1.95-1.85 (m, 1H), 1.81-1.53 (m, 5H). ^{13}C NMR (101 MHz, CDCl_3) δ 138.03, 132.69, 129.25, 128.99, 127.56, 122.94, 98.62, 68.79, 62.39, 30.74, 25.67, 19.54.

2-(acetoxymethyl)phenyl acetylene (25)

The following procedure was adapted from Kurita *et al.*⁷⁷ An oven-dried 100 mL round bottom flask was equipped with a magnetic stir bar, rubber septum and nitrogen inlet. 2-Ethynylbenzyl alcohol (1.2 g, 8.2 mmol) and 4-dimethylaminopyridine (0.95 g, 8.2 mmol)

were added by briefly removing the septum. Pyridine (1.6 mL, 19.7 mmol) was then charged to the flask followed by CH₂Cl₂ (30 mL). The reaction mixture was then cooled to 0 °C via an ice water bath. Acetic anhydride (2.4 mL, 25 mmol) was added slowly and allowed to stir at 0 °C for 30 minutes. The reaction mixture was warmed to r.t and equipped with a nitrogen balloon via glass inlet adapter to stir overnight. The reaction was quenched with 1 M HCl (50 mL) and transferred the solution to a separatory funnel using diethyl ether (100 mL). The organic layer was washed with water (3 × 100 mL) and brine (100 mL). The ether layer was dried over magnesium sulfate and filtered by gravity. The filtrate was concentrated by rotary evaporation to afford the target compound **25** as a red-orange liquid (1.9 g). ¹H NMR (400 MHz, CDCl₃) δ 7.52 (d, 1H), 7.41-7.34 (m, 2H), 7.28 (t, 1H), 5.29 (s, 2H), 3.32 (s, 1H), 2.13 (s, 3H). ¹³C NMR (101 MHz, CDCl₃) δ 171.02, 138.35, 133.12, 129.23, 128.47, 121.66, 82.41, 80.99, 64.74, 21.11.

tert-butyl(2-ethynylbenzyloxy)dimethylsilane (26)

Compound **26** was prepared using a procedure developed by Odedra, Datta and Liu.¹⁰ An oven-dried 10 mL round bottom flask was equipped with a magnetic stirrer, rubber septum and nitrogen gas inlet. 2-Ethynylbenzyl alcohol (0.20 g, 1.4 mmol) and imidazole (0.15 g, 2.1 mmol) were dissolved in dimethylformamide (2 mL) and transferred to the flask via syringe. The solution was cooled to 0 °C in an ice water bath. Upon addition of TBDMSCl (0.26 g, 1.6 mmol), the solution became cloudy and light yellow. The reaction mixture was warmed to ambient temperature and stirred overnight with nitrogen balloon inlet. Water (5 mL) was added to the flask and was stirred for 15 minutes. The solution was transferred with EtOAc (10 mL) to a separatory funnel. The organic layer was washed with water (3 × 15 mL) and brine (10 mL) and dried over magnesium sulfate.

Once filtered by gravity and the organic layer was concentrated by rotary evaporation (ca. 12 Torr) to afford **26** as a pale yellow oil, without further purification (0.13 g, 38%). ^1H NMR (400 MHz, CDCl_3) δ 7.56 (d, 1H), 7.45 (d, 1H), 7.38 (t, 1H), 7.20 (t, 1H), 4.90 (s, 2H), 3.30 (s, 1H), 0.96 (s, 1H), 0.12 (s, 1H). ^{13}C NMR (101 MHz, CDCl_3) δ 149.14, 137.59, 134.30, 131.72, 131.05, 124.05, 87.30, 86.36, 68.41, 31.28, 23.74, 0.00.

Attempts at *ortho*-xylallene by Hydride Addition

(1) An oven dried 10 mL round bottom flask was equipped with a magnetic stir bar and purged with nitrogen. 2-(acetoxymethyl)phenyl acetylene (0.10 mL, 0.57 mmol) was charged to the flask followed by sodium borohydride (22 mg, 0.55 mmol) dissolved in methanol (2 mL). Gas evolved slightly from the reaction mixture and became light yellow as it stirred for 1 hour. The reaction was quenched with 3M NaOH (1 mL) and water (5 mL). The solution was transferred to a separatory funnel with CH_2Cl_2 . The organic layer was partitioned and washed with water (3×15 mL) and brine (10 mL) then dried over magnesium sulfate. The filtrate was concentrated to a light yellow solid which was later determined to be 2-ethynylbenzyl alcohol by ^1H NMR analysis.

(2) The above procedure was carried out using tetrahydrofuran (2 mL) as the solvent. The reaction remained light yellow without formation of gas upon addition of NaBH_4 dissolved in THF. Using thin layer chromatography the reaction was found to contain only starting material after 4 hours. Reflux was started and the reaction mixture became orange over 24 hours. Starting material was recovered from subsequent aqueous work up using 3M NaOH and diethyl ether as the extraction solvent.

(3) The same procedure was followed when using 1,4-dioxane. When sodium borohydride was added there was no change in the reaction mixture. The reaction was monitored by thin layer chromatography. After 4 hours analysis showed no formation of product. The water-cooled condenser was added and the solution was

refluxed for 24 hours. Upon aqueous work up, the crude product mixture was observed to contain the acetate starting material as well as the corresponding alcohol however no indication of chrysene was observed.

(4) tert-butyl(2-Ethynylbenzyloxy)dimethylsilane (**26**) was treated under analogous conditions. The resultant yellow mixture was stirred at room temperature for 4 h. With no conversion to products observed by TLC analysis, the reaction mixture was subjected to reflux. The reaction was monitored at reflux for 2 days and was ultimately quenched to afford a quantitative recovery of starting material.

Chapter III

2-phenylnaphthalene (27)

The procedure for Suzuki coupling was applied to the synthesis of 2-phenylnaphthalene. Purification by column chromatography (hexanes, 2% CH₂Cl₂/hexanes, 4%, 6% × 200 mL) allowed for isolation of the title compound (**29**) as a white crystalline solid (m.p 99-101 °C, *lit.* 105 °C) (1.45 g, 73 % yield). ¹H NMR (400 MHz, CDCl₃) δ 8.05 (s, 1H), 7.89 (m, 3H), 7.74 (t, 3H), 7.49 (t, 4H), 7.39 (t, 1H). ¹³C NMR (101 MHz, CDCl₃) δ 141.34, 138.77, 133.88, 132.82, 129.07, 128.63, 128.41, 127.86, 127.65, 127.57, 126.50, 126.15, 126.02, 125.82.

1,2'-binaphthalene (28)

The following procedure was adapted from Cheon and coworkers.⁷⁸ An oven-dried 25 mL round bottom flask was equipped with a magnetic stir bar, rubber septum and nitrogen gas inlet. Previously prepared 1-naphthyl boronic acid (0.54 g, 3.1 mmol) was dissolved in 3 mL D.I water and was charged to the flask. Potassium carbonate (0.50 g,

3.6 mmol) was then added quickly by removing the septum. 95% Ethanol was charged to the flask (6 mL) before 2-bromonaphthalene (0.51 g, 2.4 mmol) and $\text{Pd(PPh}_3)_4$ (0.14 mg, 0.12 mmol) were added. The reaction mixture was refluxed for 24 hours then cooled to room temperature. The reaction was quenched with 1M NaOH (5 mL) and the solution was transferred to a separatory funnel using CH_2Cl_2 . The organic layer was washed with water (3 \times 50 mL), brine (50 mL) and dried over sodium sulfate. Once concentrated by rotary evaporation, the brown oil was filtered over silica gel and eluted with hexanes. 1,2'-Binaphthalene (**28**) was isolated as a white solid (m.p. 74-76 °C *lit.* 75-76 °C) after further purification by flash chromatography using hexanes (0.40 g, 66% yield). ^1H NMR (400 MHz, CDCl_3) δ 7.95-7.87 (m, 7H), 7.64(d, 1H), 7.59-7.45 (m, 5H), 7.41 (t, 1H). ^{13}C NMR (101 MHz, CDCl_3) δ 140.42, 138.57, 134.08, 133.67, 132.83, 132.01, 128.99, 128.74, 128.58, 128.33, 128.01, 127.91, 127.50, 126.56, 126.35, 126.30, 126.08, 125.68.

2,2'-binaphthalene (29)

This procedure was adapted from the one above in conjunction with microwave parameters for Suzuki coupling reactions reported by Hayes.²⁹ A 35 mL vial was equipped with a stir bar, rubber septum and nitrogen gas inlet. 2-Bromonaphthalene (0.21 g, 0.97 mmol) was added to the vial which was then purged with nitrogen. Toluene (7 mL) was then charged to the vial followed by methanol (2 mL). 2-Naphthylboronic acid (0.32 g, 1.9 mmol) and $\text{Pd(PPh}_3)_4$ (56 mg, 0.05 mmol) were added quickly by removing the septum. While stirring, 2M K_2CO_3 (2 mL) was added dropwise via syringe. A white precipitate was observed within the yellow reaction mixture. The vial was purged and capped before being placed in the microwave reactor at the following parameters (T=150 °C, R= 20 min, H= 60 min, 200W). The reaction mixture was cooled to room temperature and transferred to a separatory funnel. The product was extracted with

CH₂Cl₂ (50 mL) then washed with water (3 × 50 mL) and brine (50 mL) before being dried over Na₂SO₄. The solution was filtered by gravity and concentrated under reduced pressure to afford a crystalline solid containing **28** and naphthalene. The desired product was purified by column chromatography using a hexane and EtOAc gradient to afford 2,2'-binaphthalene as a white crystalline solid (m.p. 184-185 °C, *lit.* 185-186 °C) (0.21 g, 86% yield). ¹H NMR (400 MHz, CDCl₃) δ 8.18 (s, 2H), 7.96 (m, 4H), 7.89 (m, 4H), 7.55-7.48 (m, 4H). ¹³C NMR (101 MHz, CDCl₃) δ 138.64, 133.96, 132.88, 128.75, 128.46, 127.90, 126.58, 126.34, 126.24, 125.96.

Rearrangement at 150 °C (Microwave Procedure)

A. *ortho*-Terphenyl. A 10 mL vial was equipped with a stir bar and rubber septum and purged with nitrogen gas. *o*-Terphenyl (0.10 g, 4.3 mmol) was added followed by DCE (1 mL). Trifluoromethanesulfonic acid (80 µL, 8.6 mmol) was then added via syringe and the solution became orange-yellow. The vial was purged and capped before being placed in the reactor (150 °C, 300 W, 30 min). The reaction was cooled to room temperature and saturated sodium bicarbonate (3 mL) was added to the vial. The organic layer was washed with water (3 × 20 mL) and brine (15 mL) then dried over sodium sulfate. The filtrate was concentrated to a yellow solid under reduced pressure. By capillary GC analysis the mixture was found to contain *ortho* (2%), *meta* (94%), and *para* (4%) terphenyl isomers. This distribution was confirmed by ¹H NMR analysis.

B. 1-Phenylnaphthalene. The same procedure was carried out with 1-phenylnaphthalene. Upon addition of triflic acid the solution became bright orange. Capillary GC analysis of the recovered material (93%) showed 2-phenylnaphthalene (**27**) as the major isomer (95%) and 1-phenylnaphthalene (4%).

C. *1,1'-Binaphthalene*. When 1,1'-binaphthalene was subjected to the above conditions addition of triflic acid produced a violet reaction mixture. 2,2'-Binaphthalene was obtained pure by ^1H NMR and capillary GC analysis (89% recovery). Under more harsh conditions (neat TFSA, 200 °C) 1,1'-binaphthalene was shown to form perylene (**32**) (44% recovery).

Rearrangements at 80 °C (Reflux in 1,2-DCE)

A. *ortho*-Terphenyl. An oven dried 25 mL 2-neck round bottom flask was equipped with a stir bar, water-cooled condenser and rubber septum. The condenser was fitted with an adapter and open to a line of nitrogen. *o*-Terphenyl (101 mg, 0.43 mmol) was dissolved in 2 mL of 1,2-DCE and transferred to the flask via syringe. An additional 2 mL of DCE was then charged to the reaction. TFSA (389 μL , 4.3 mmol) was then added via syringe and the solution became orange in color. As the reaction mixture reached reflux it darkened in color to black over the course of 5 days. Aliquots (0.1 mL) were taken by syringe; products were extracted using diethyl ether and washed with small portions of saturated sodium bicarbonate, water, and brine (1 mL each). Analysis by capillary gas chromatography showed a rapid isomerization of *ortho*-terphenyl to *meta* and then to *para*-terphenyl. This procedure was later repeated by Sarah Skraba to the extent of 14 days where aliquots were not taken until day 5. By GC analysis the product distribution did not change in the final 8 days. After aqueous work up an orange solid was isolated (67%) and was found to contain *ortho* (<1%), *meta* (70%), and *para*-terphenyl (30%).

B. *para*-Terphenyl. *p*-Terphenyl was refluxed in 1.1M TFSA in 1,2-DCE following the procedure described for *o*-terphenyl. Isomerization to *meta*-terphenyl was observed at a slower rate than compared to *ortho*-terphenyl. The reaction mixture

contained *ortho* (<1%), *meta* (62%) and *para*-terphenyl (38%) for 8 days before being quenched. An orange solid was isolated (56% recovery) from the reaction.

C. *meta*-Terphenyl. *m*-Terphenyl (0.10 g, 0.43 mmol) was subjected to analogous conditions, however isomerization was observed to occur at a much slower rate relative to the *ortho* and *para* isomers. A product distribution of *ortho* (<1%), *meta* (71%) and *para*-terphenyl (29%) was sustained for 8 days before the reaction was quenched. From the reaction, 59% of the material was recovered as an orange solid.

D. 1-Phenylnaphthalene. 1-Phenylnaphthalene (0.10 g, 0.49 mmol) was treated with 1.1M TFSA at 80 °C and monitored by capillary GC. A product distribution of 1-phenylnaphthalene (4%) and 2-phenyl naphthalene (96%) was observed after 30 minutes. This ratio was maintained as fluoranthene began to form irreversibly from 1-phenylnaphthalene after 1 hour. GC analysis of the reaction mixture after 4 hours showed 1-phenylnaphthalene (2%), 2-phenylnaphthalene (57%) and fluoranthene (41%). The reaction was prolonged for 7 days to observe any further chemistry. A black resin was obtained after an aqueous work up using CH₂Cl₂ as the extraction solvent. This material was chromatographed over silica gel using hexane and concentrated to a red oil (28% recovery). Analysis of the oil by capillary GC showed a mixture containing naphthalene (57%), 1-phenylnaphthalene (12%), and fluoranthene (31) (31%).

E. 1,1'-Binaphthalene. 1,1'-Binaphthalene (0.10 g, 0.39 mmol) was subjected to 1.1M TFSA in DCE at 80 °C. After 10 minutes, analysis by capillary GC showed complete isomerization of 1,1'-binaphthalene to the 2,2'-isomer without intermediate observation of 1,2'-binaphthalene. After 30 minutes analysis showed perylene as the only component. Conditions were maintained for 7 days in order to observe any further chemistry. The crude tar obtained after aqueous work up using CH₂Cl₂ was passed through a short plug of silica and eluted with hexane. The solvent

was evaporated to afford a light yellow solid (7% recovery) determined to be perylene (32) by ^1H NMR and capillary GC analysis.

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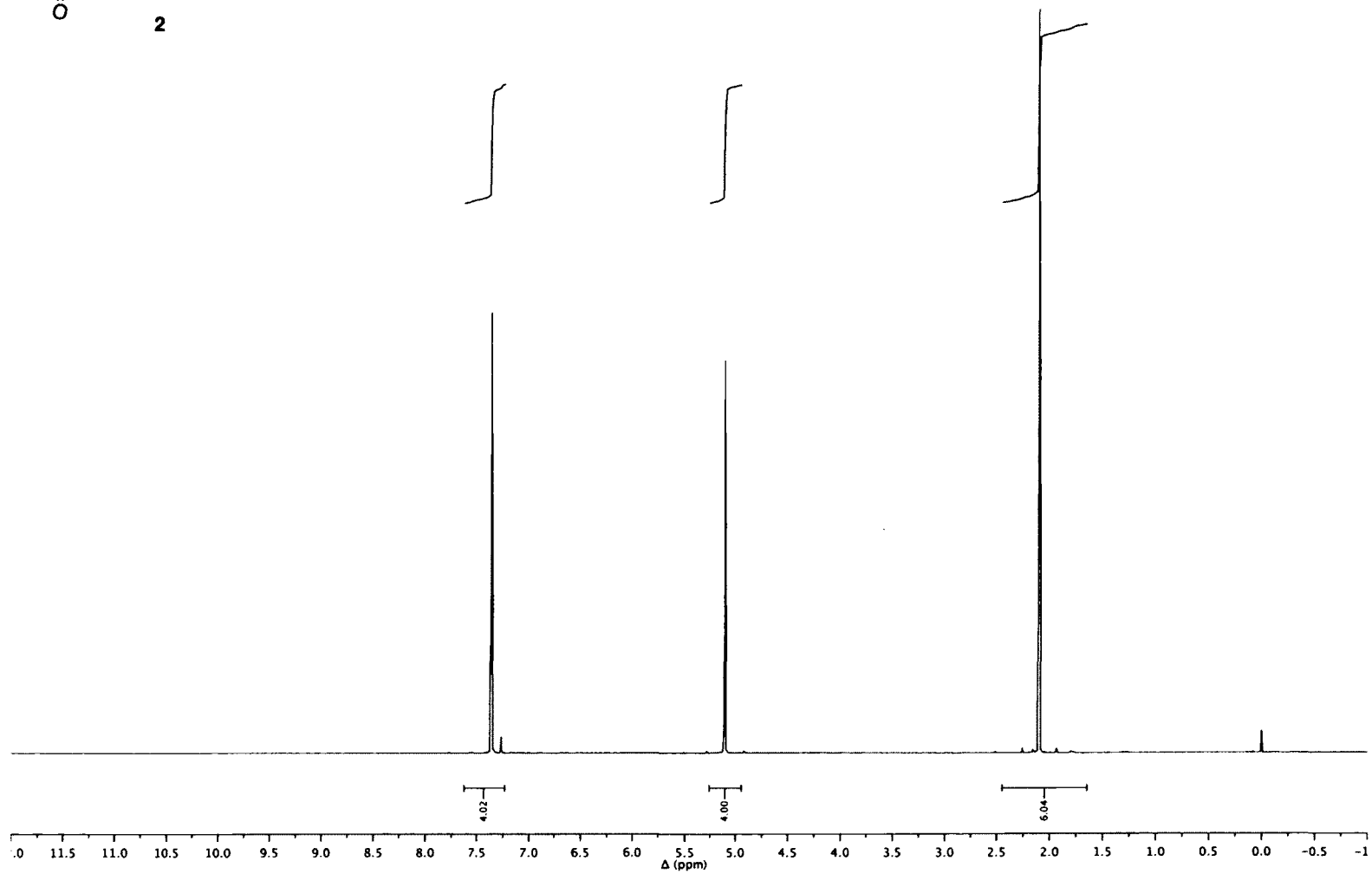
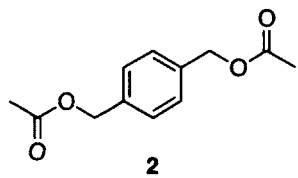
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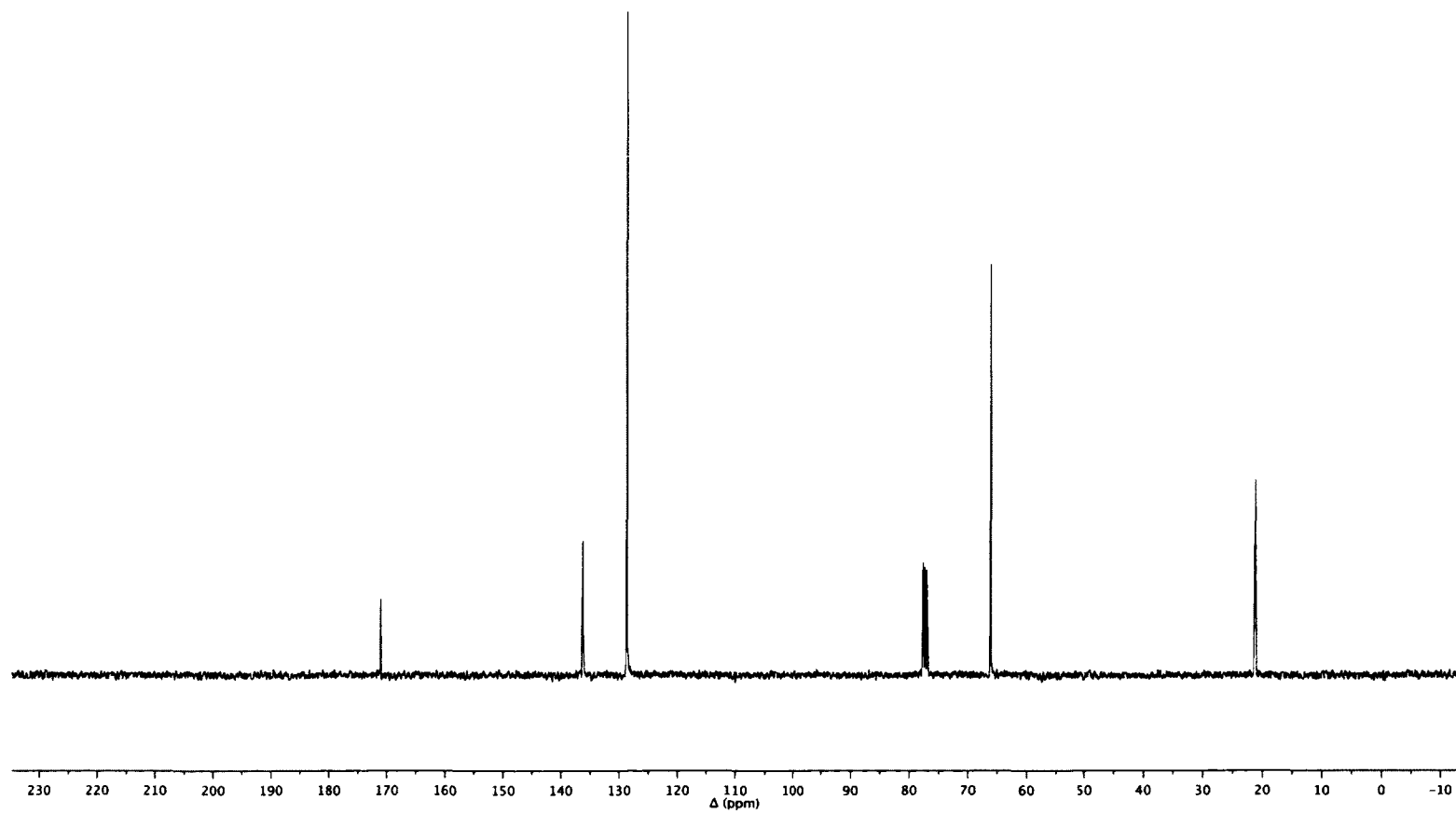
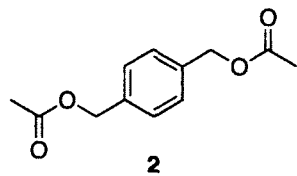
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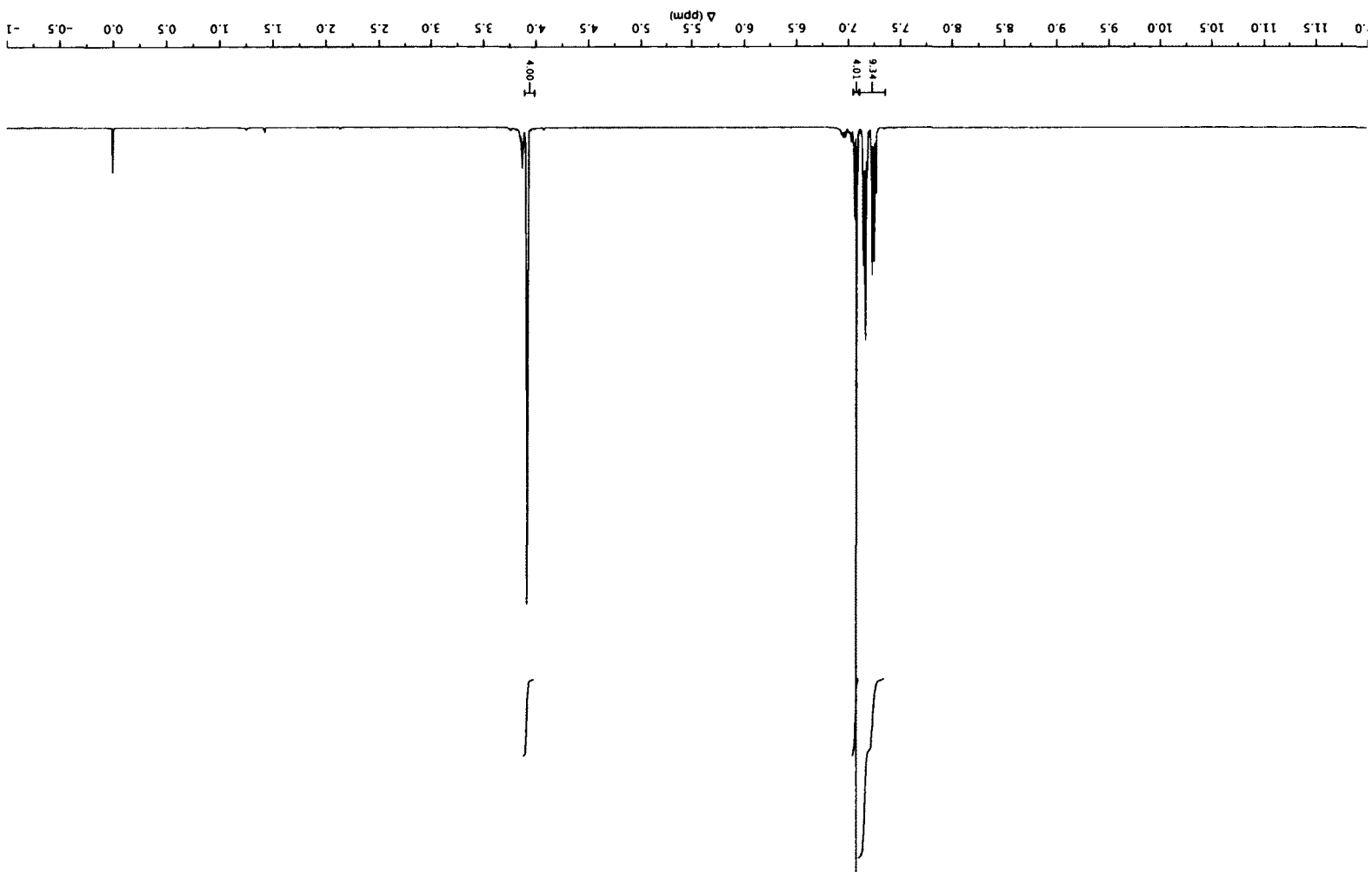
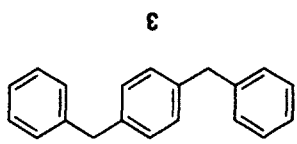
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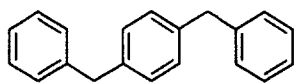
APPENDICES

APPENDIX A: Spectra

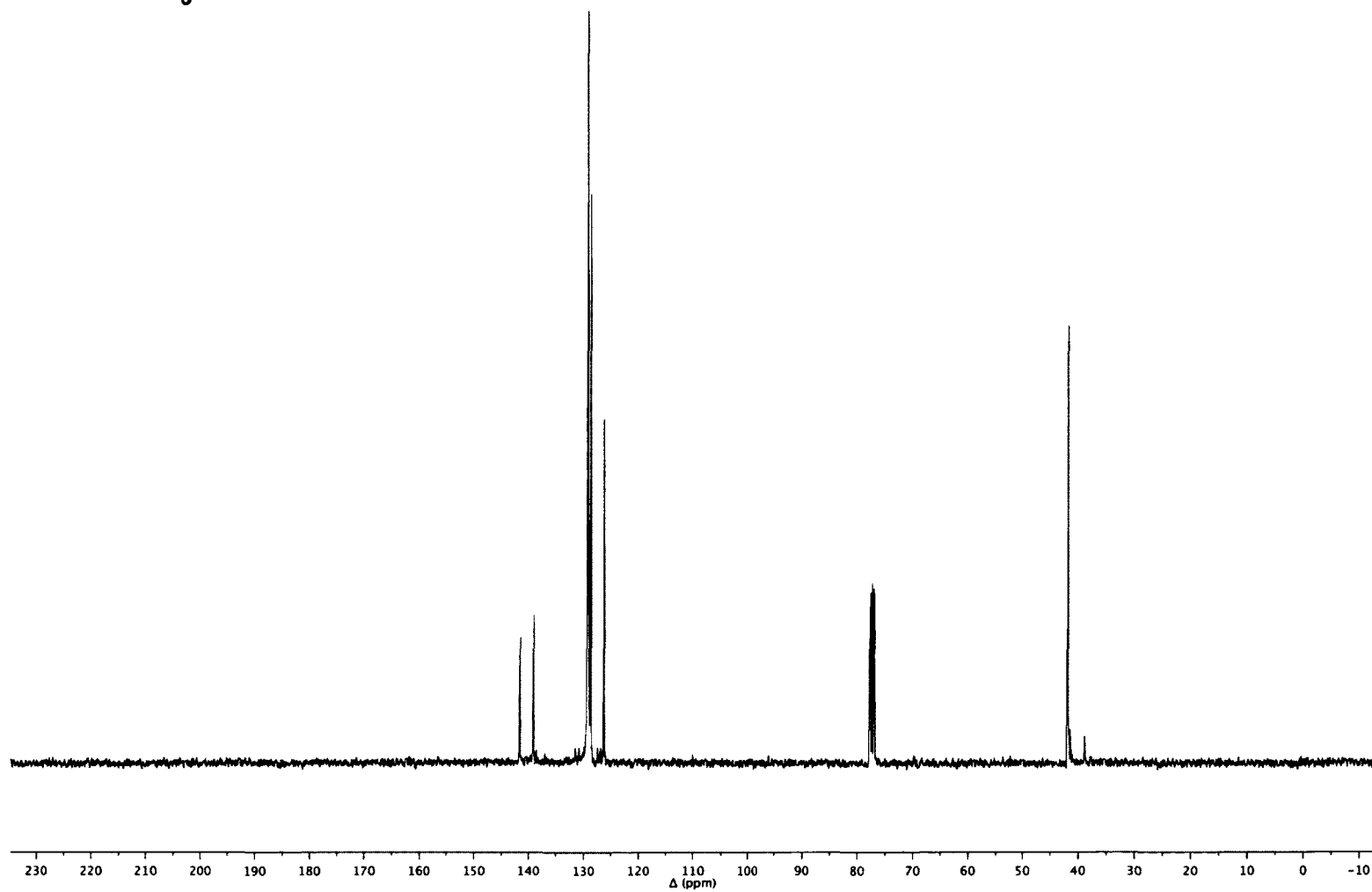


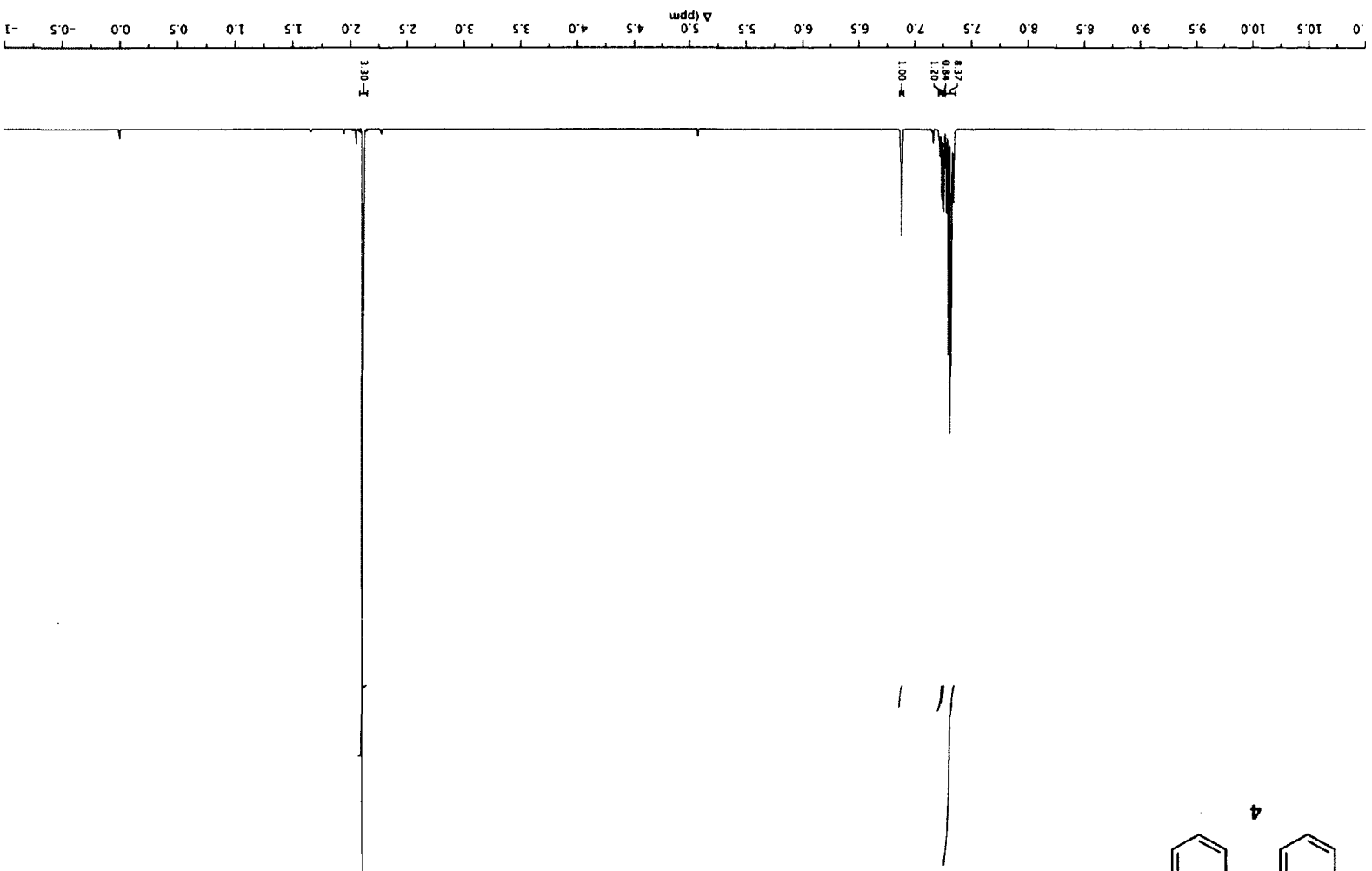
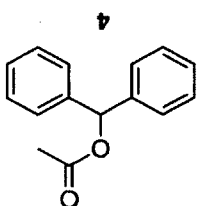


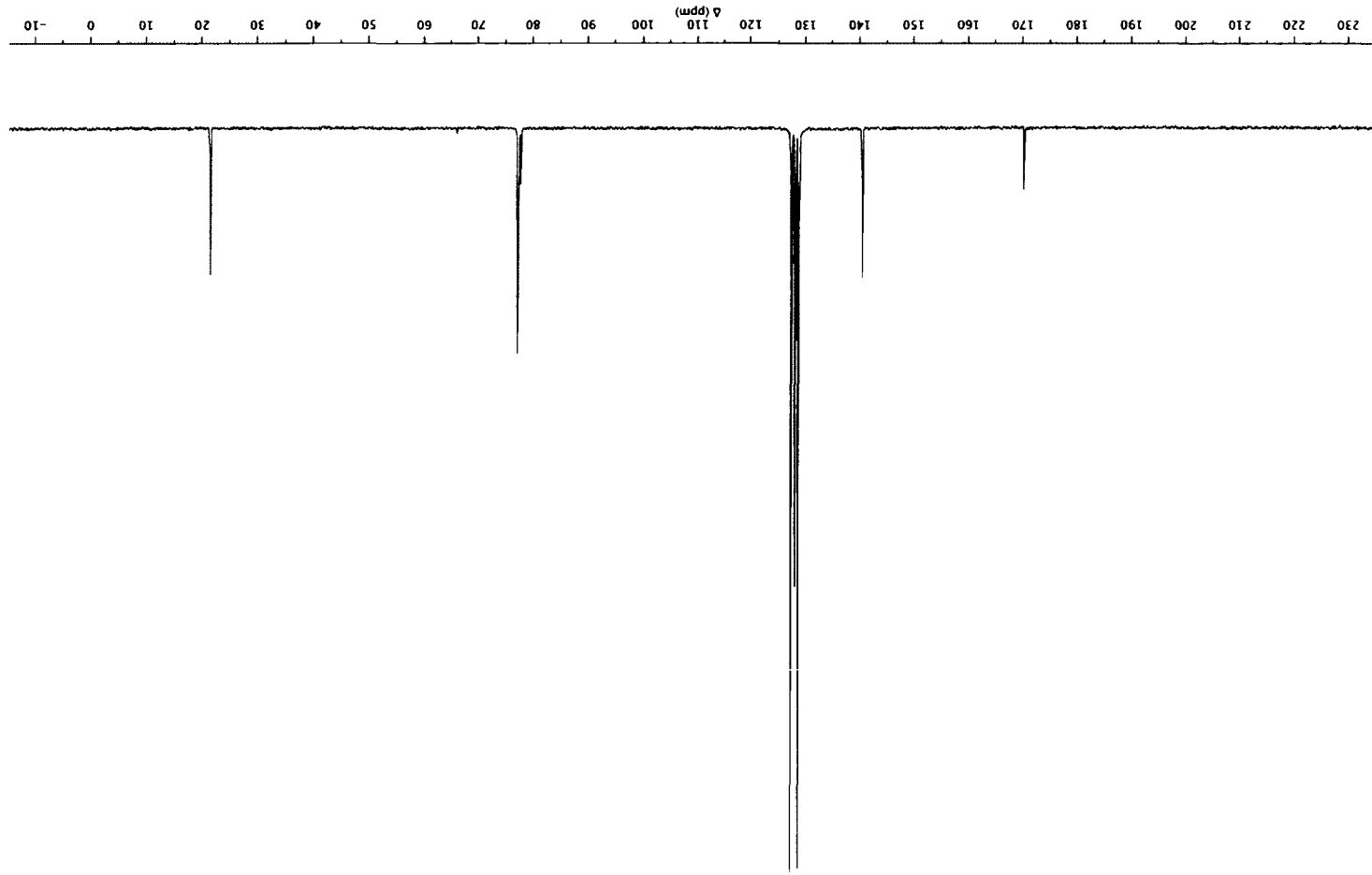
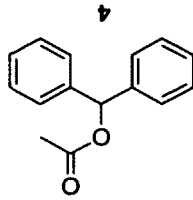


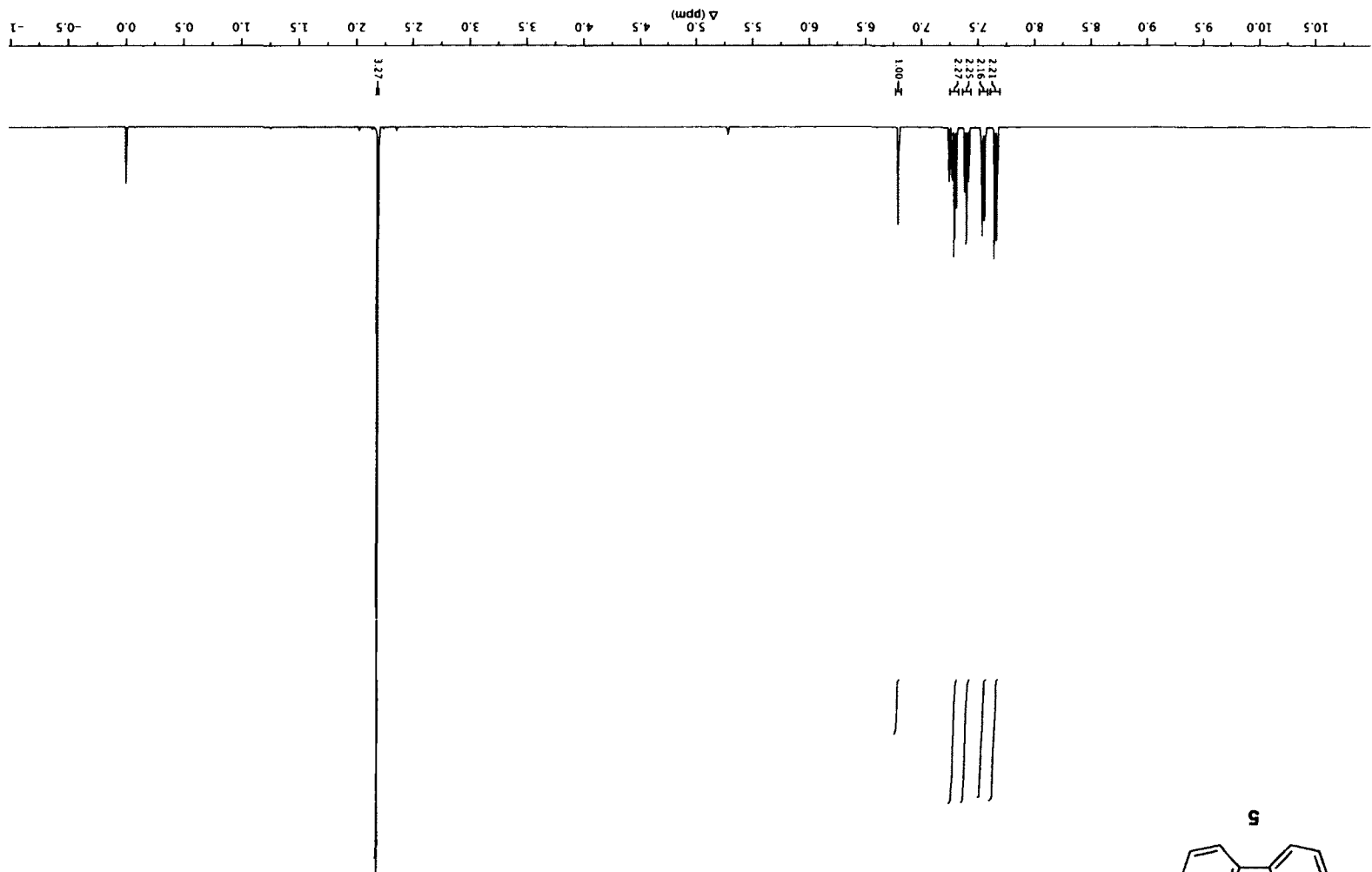
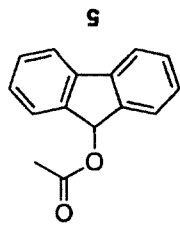


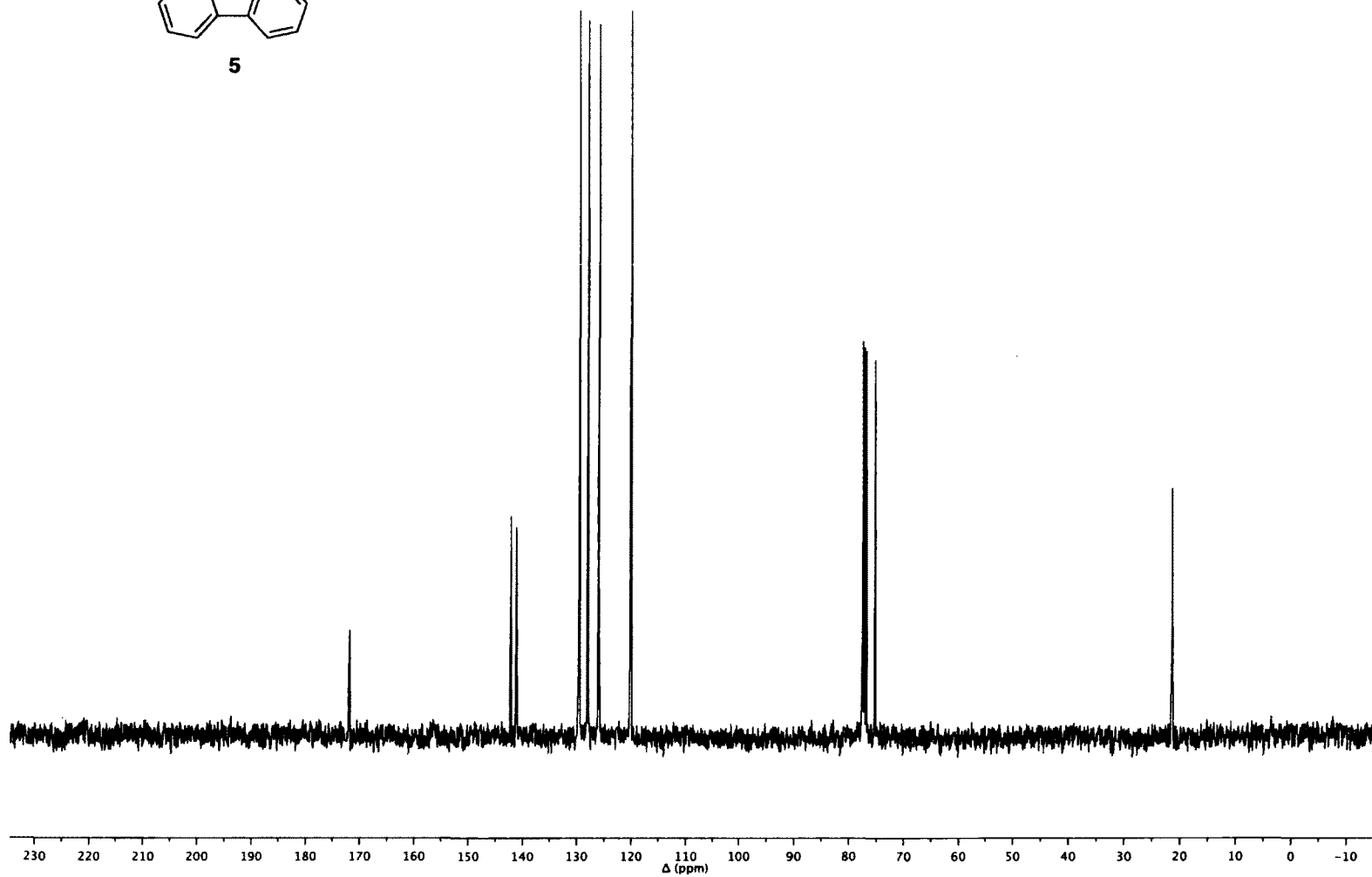
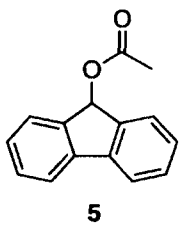
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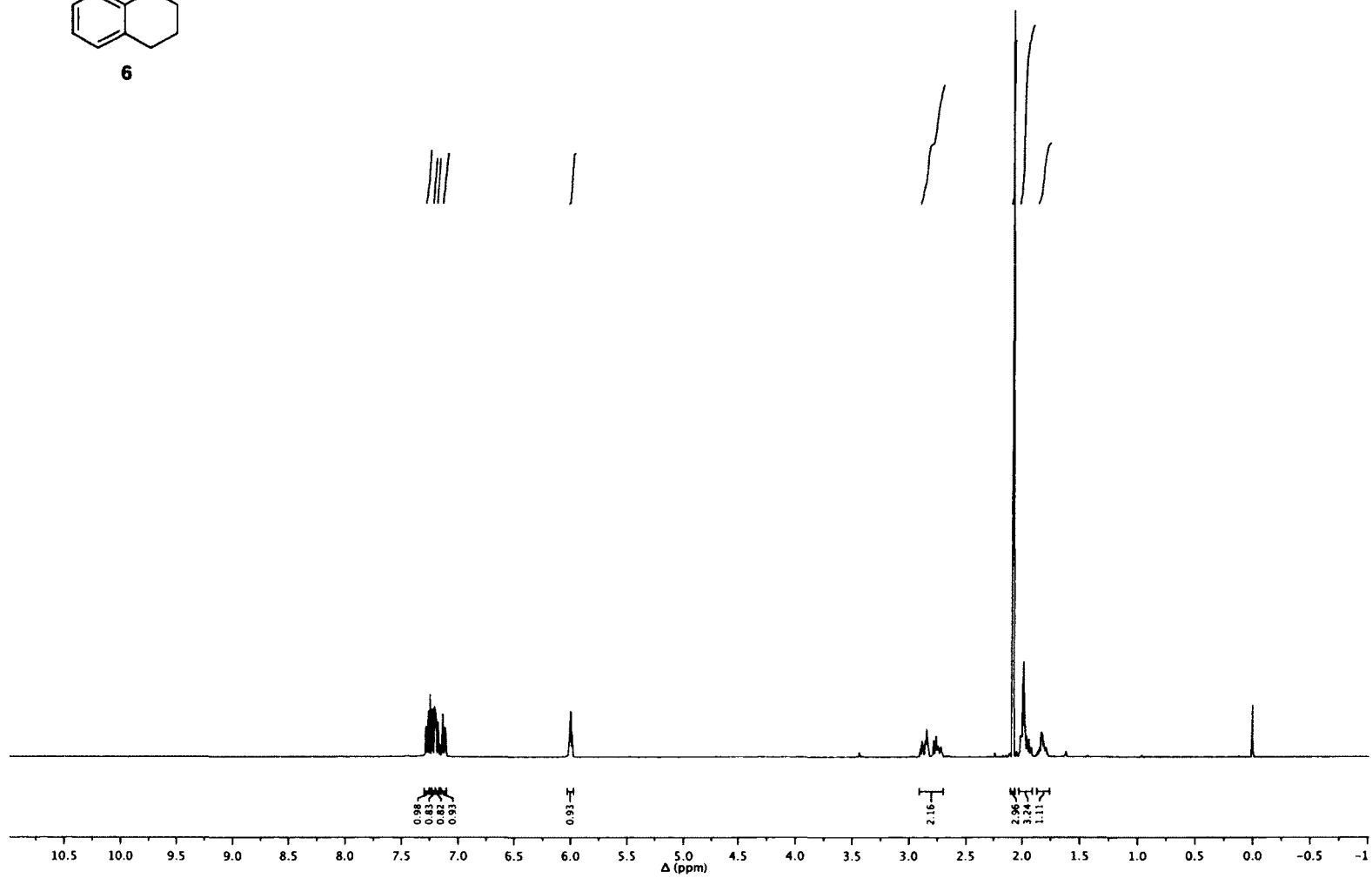
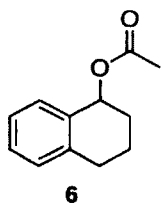


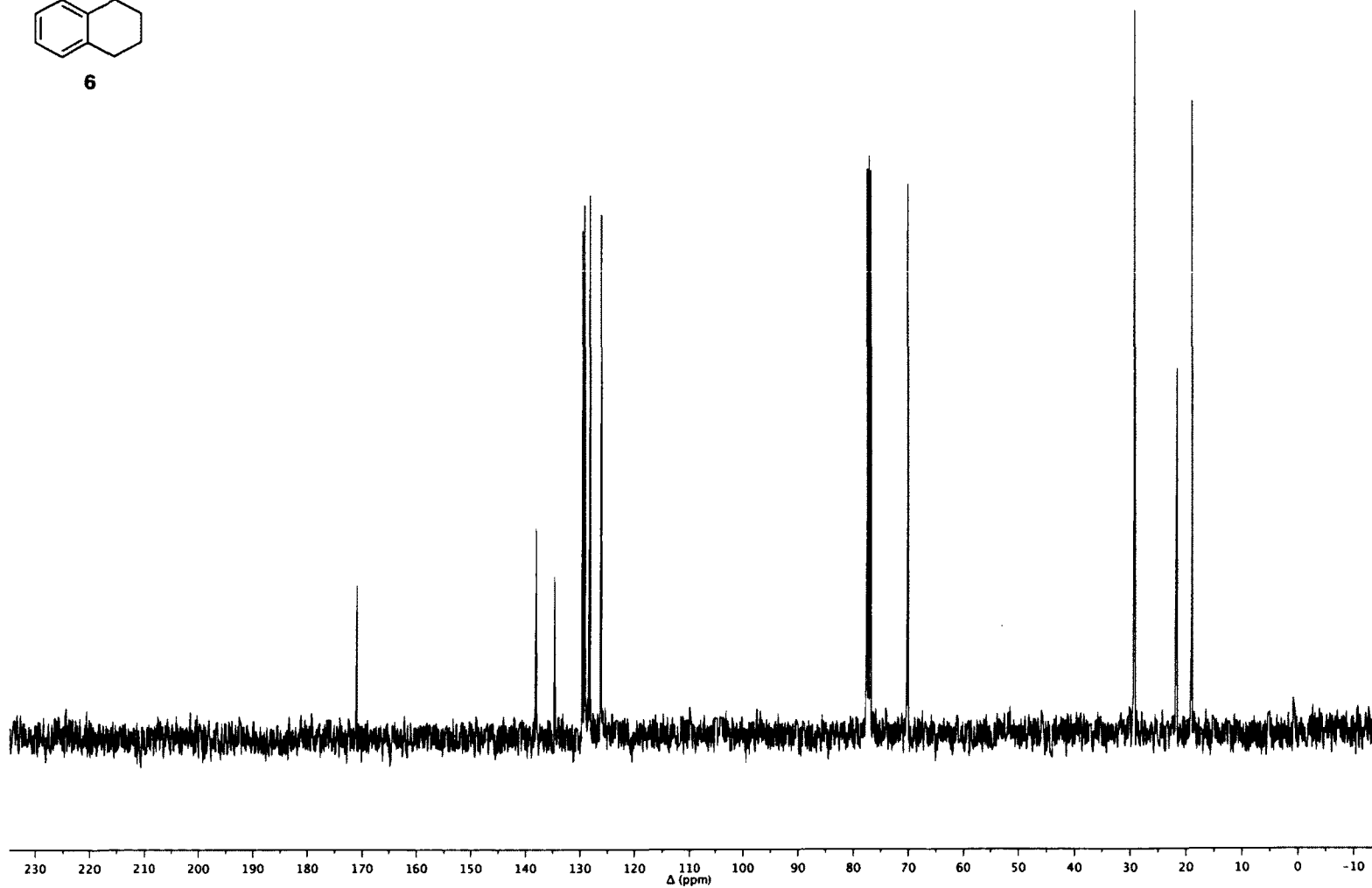
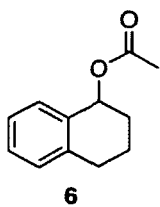


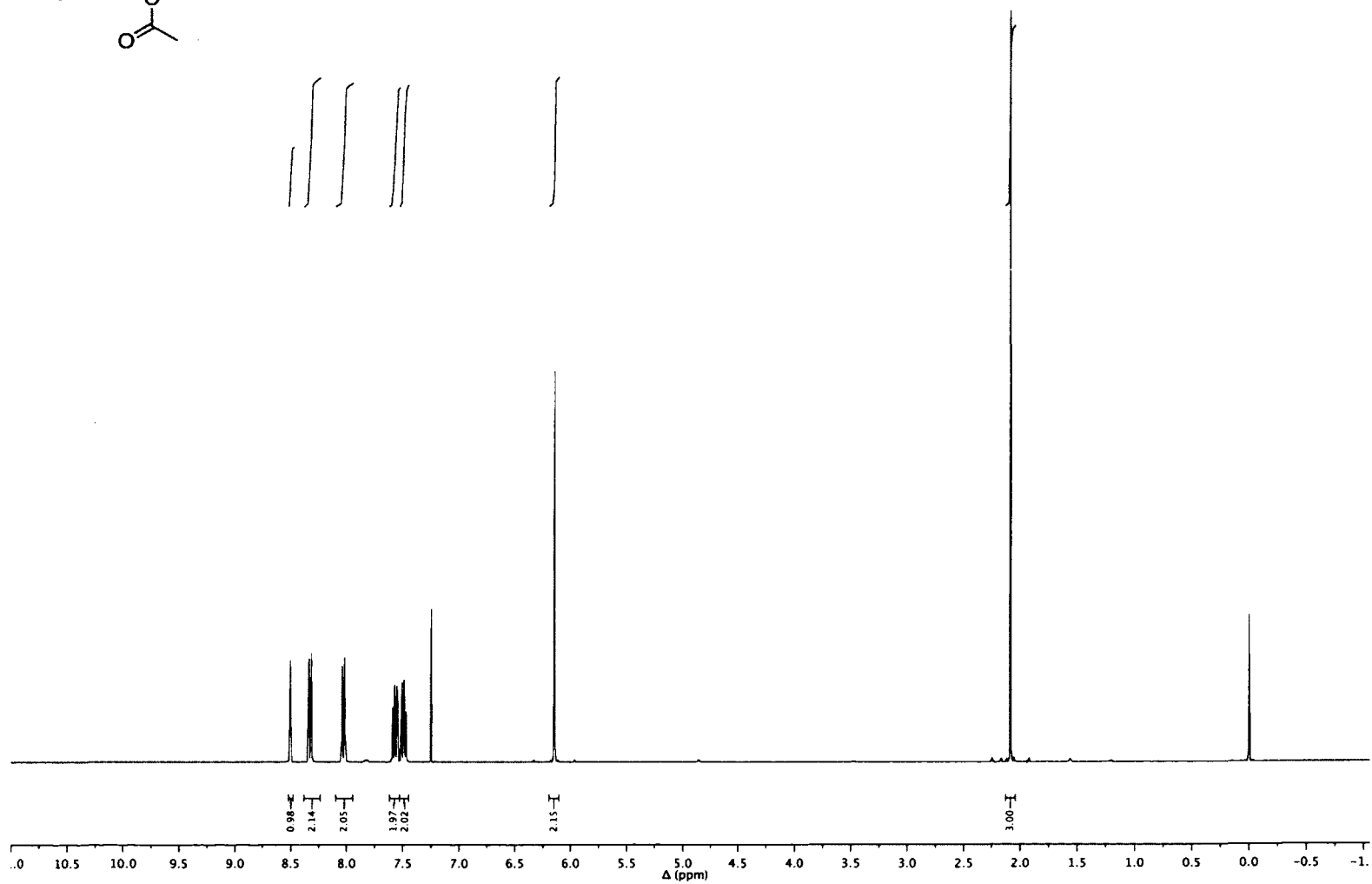
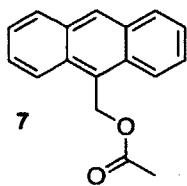


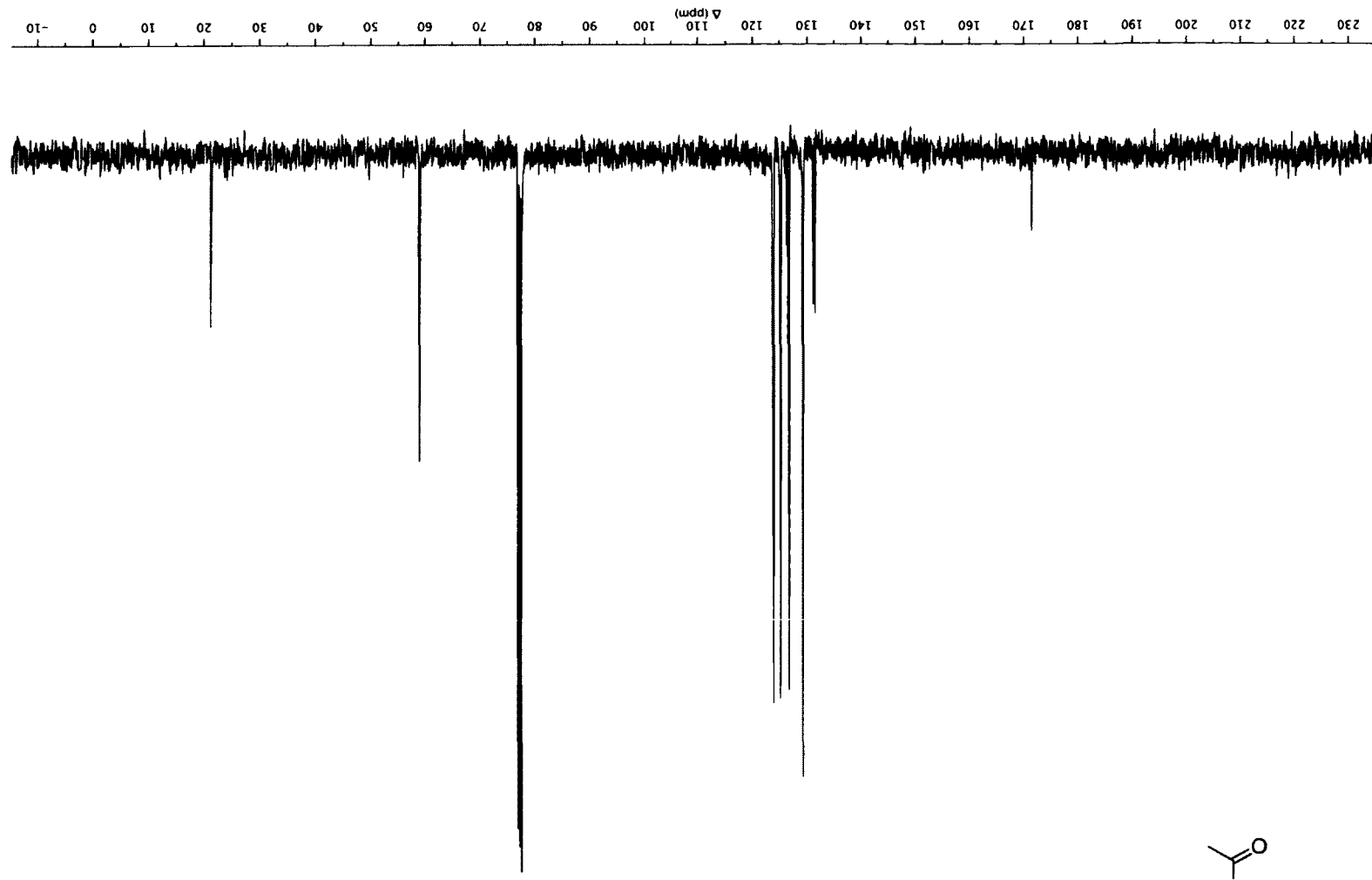
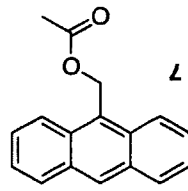


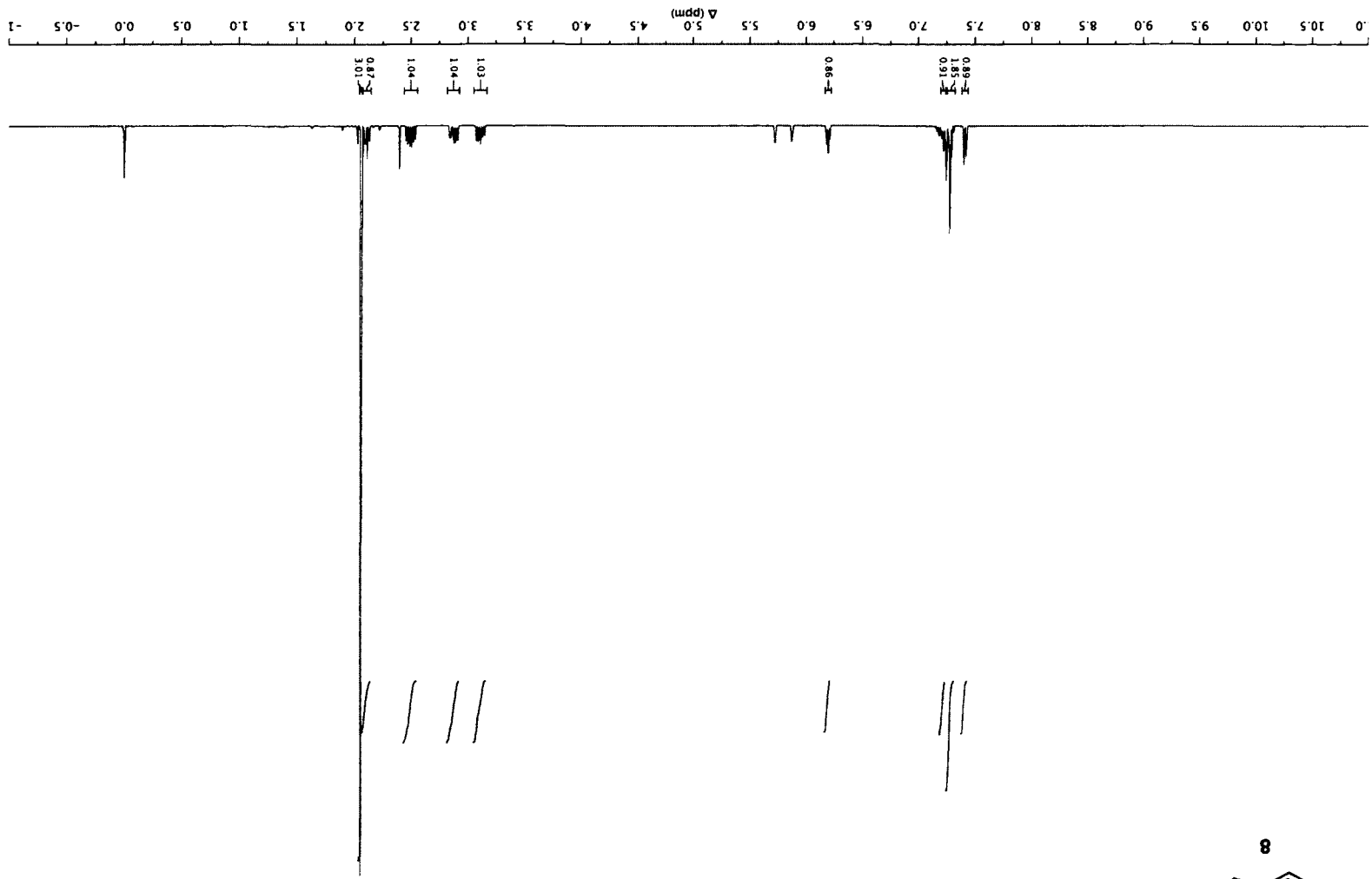
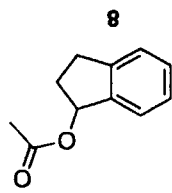


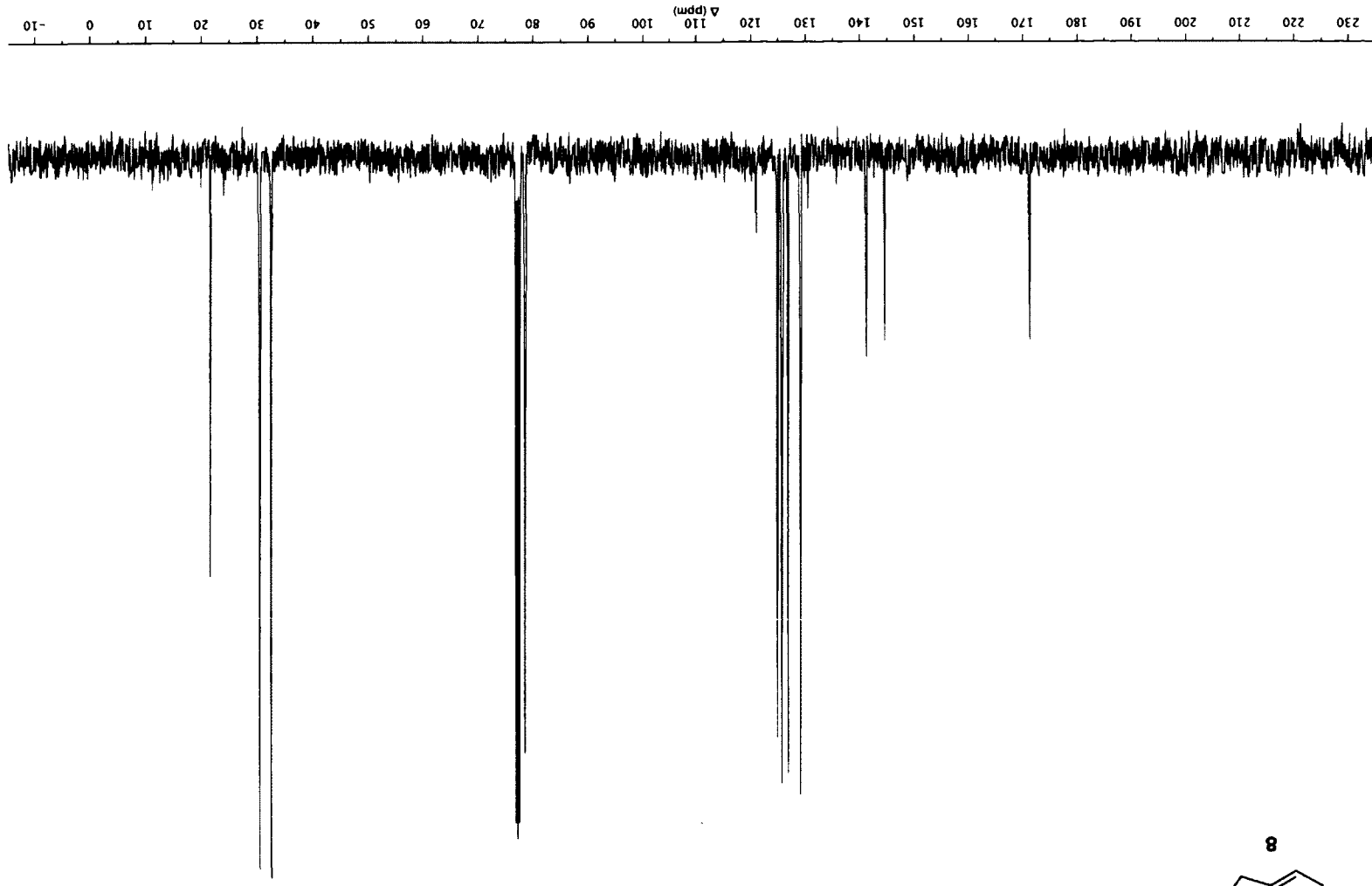
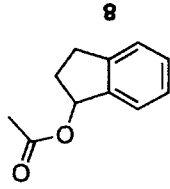


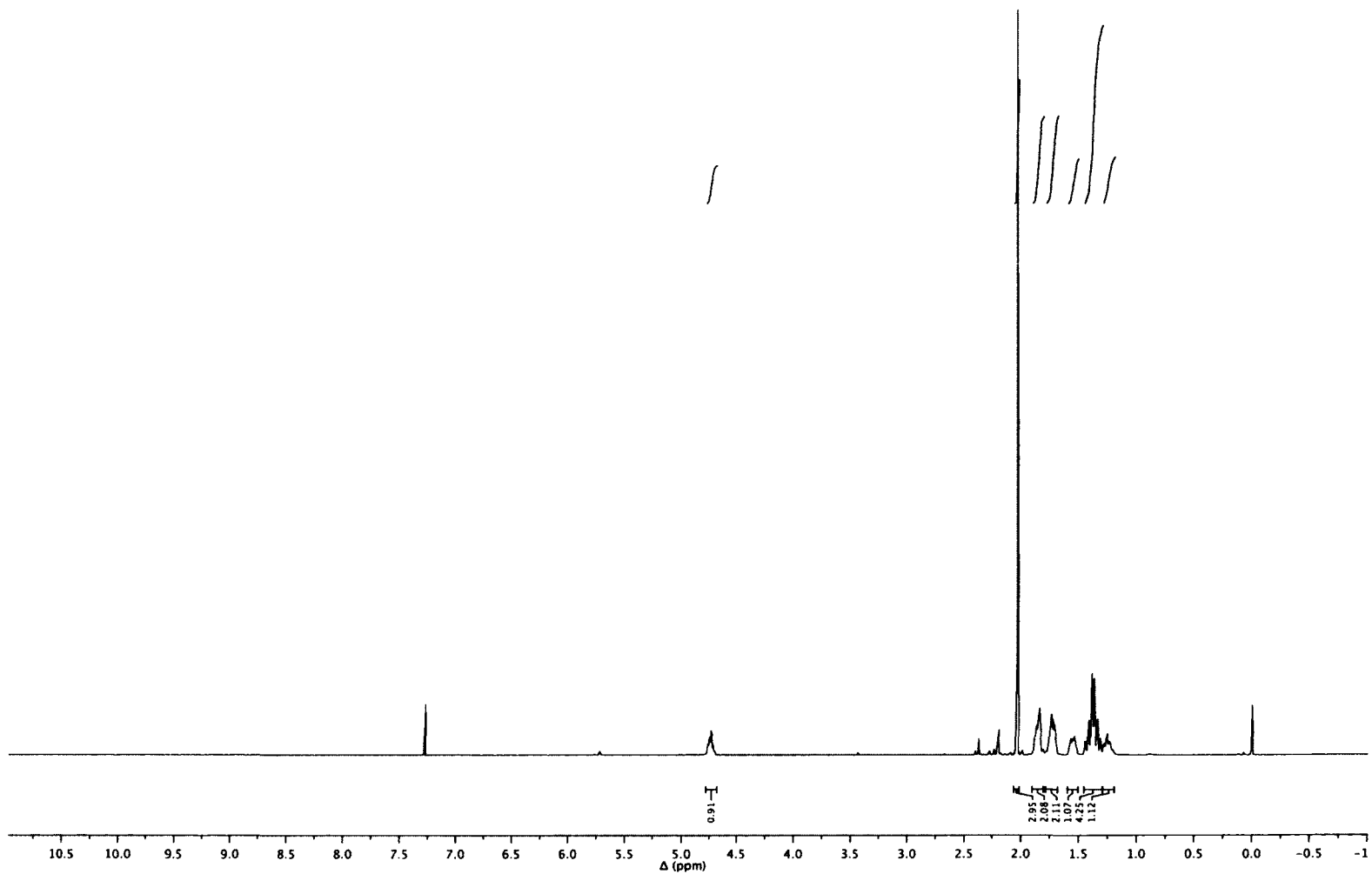
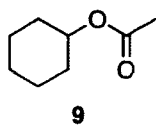


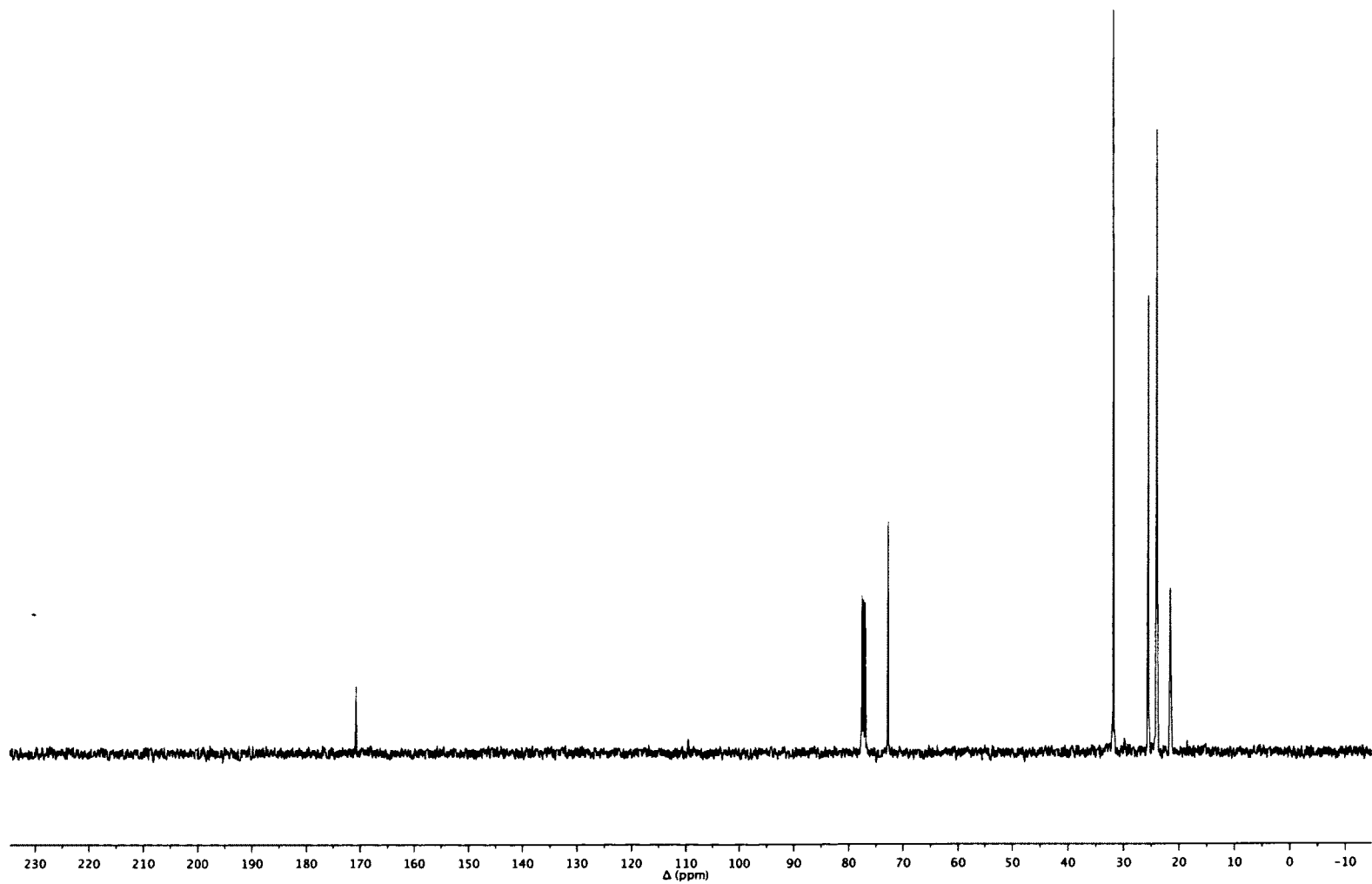
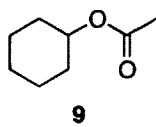


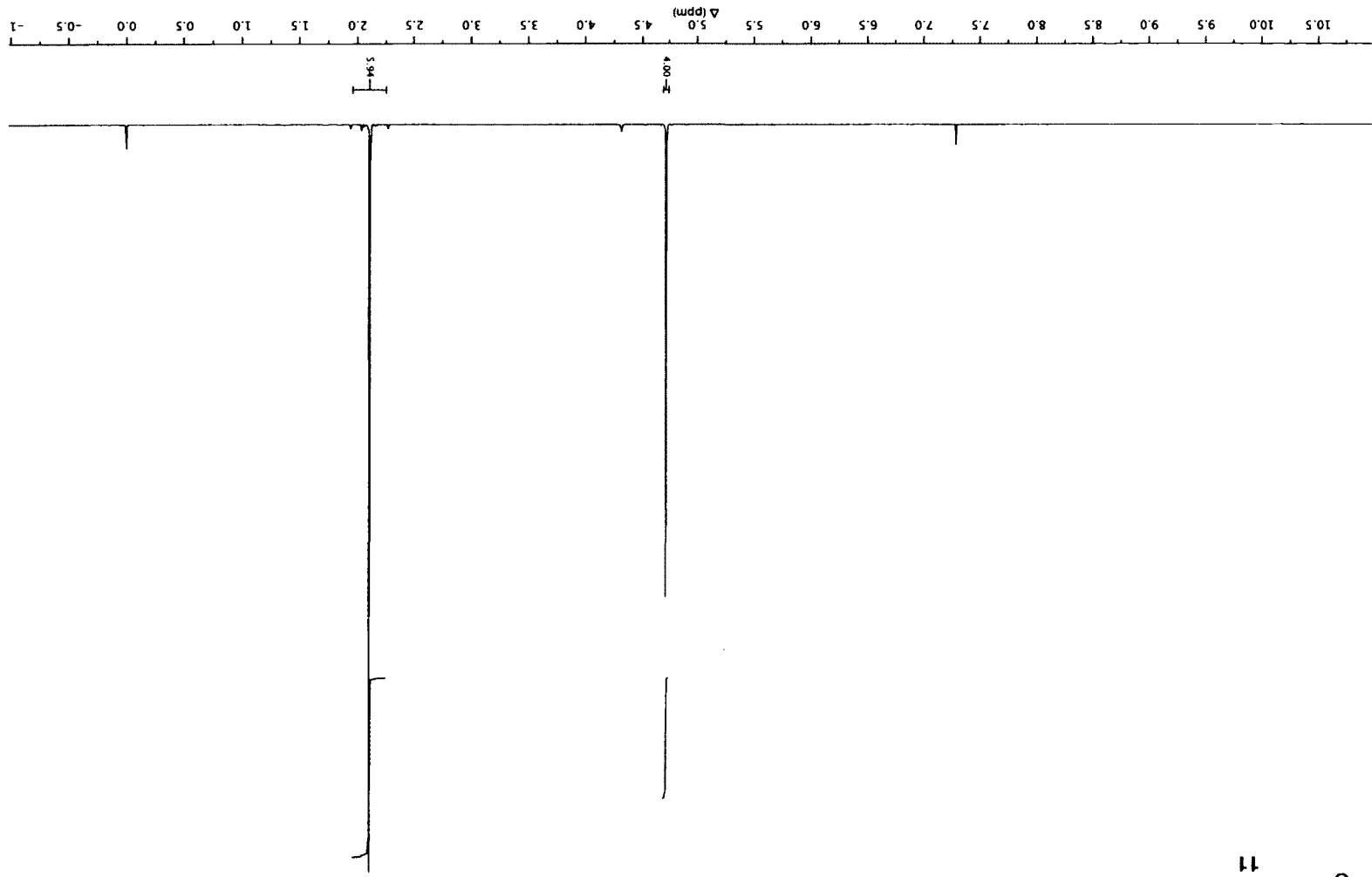
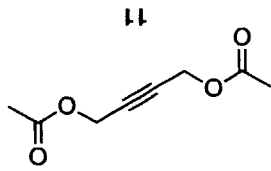


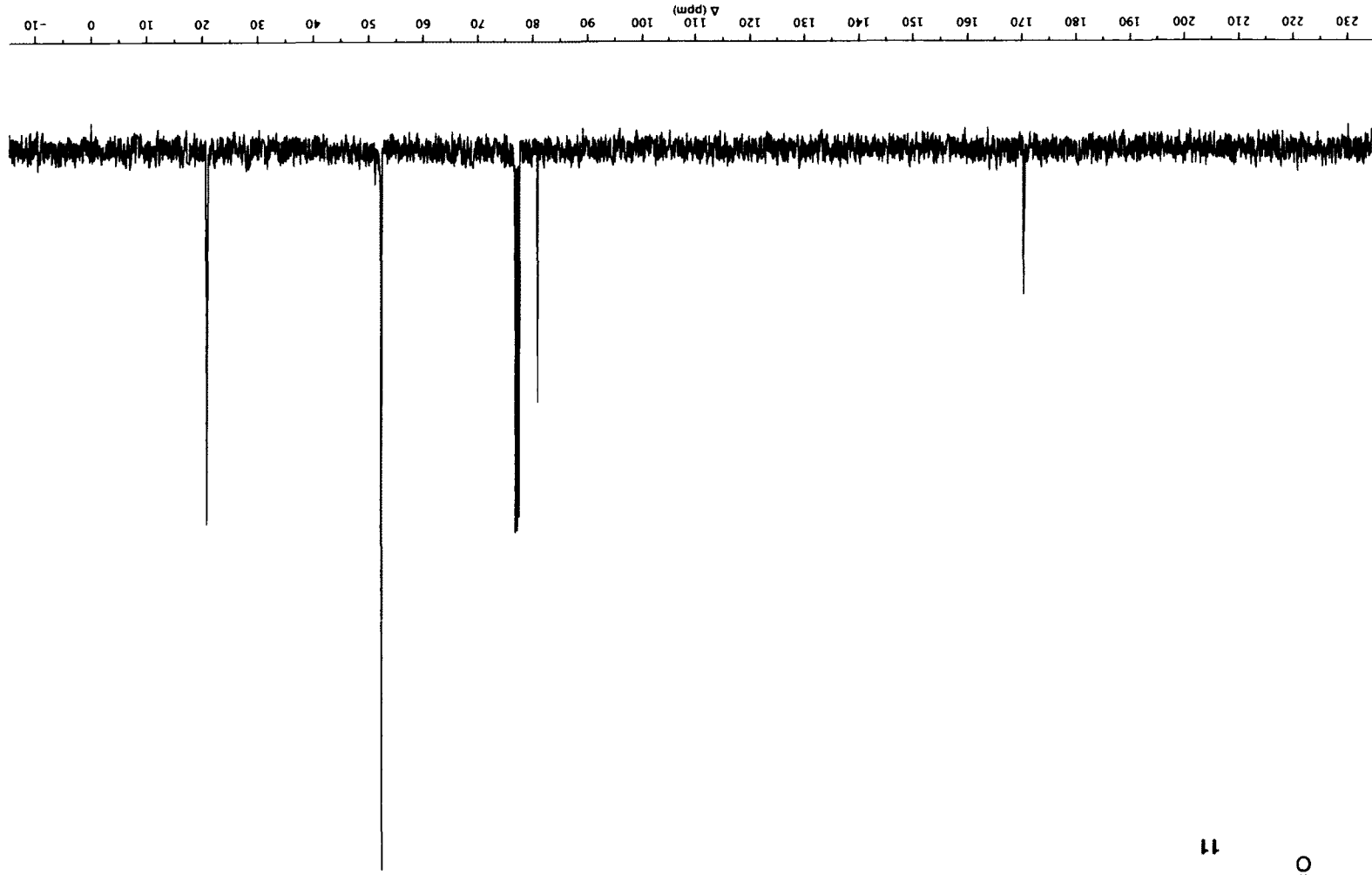
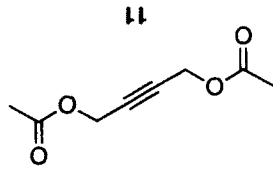


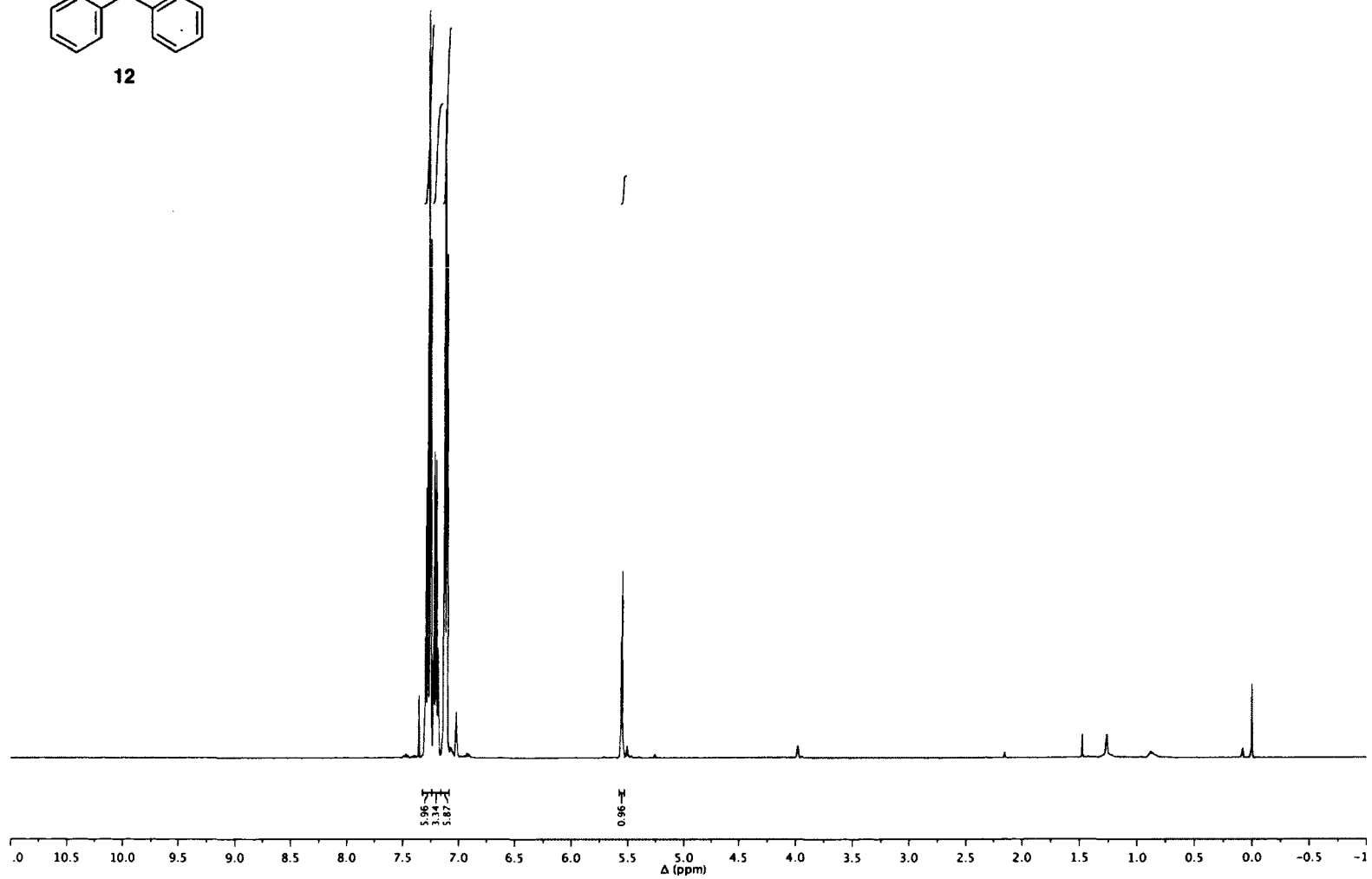
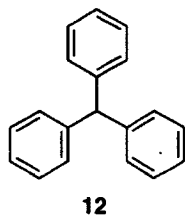


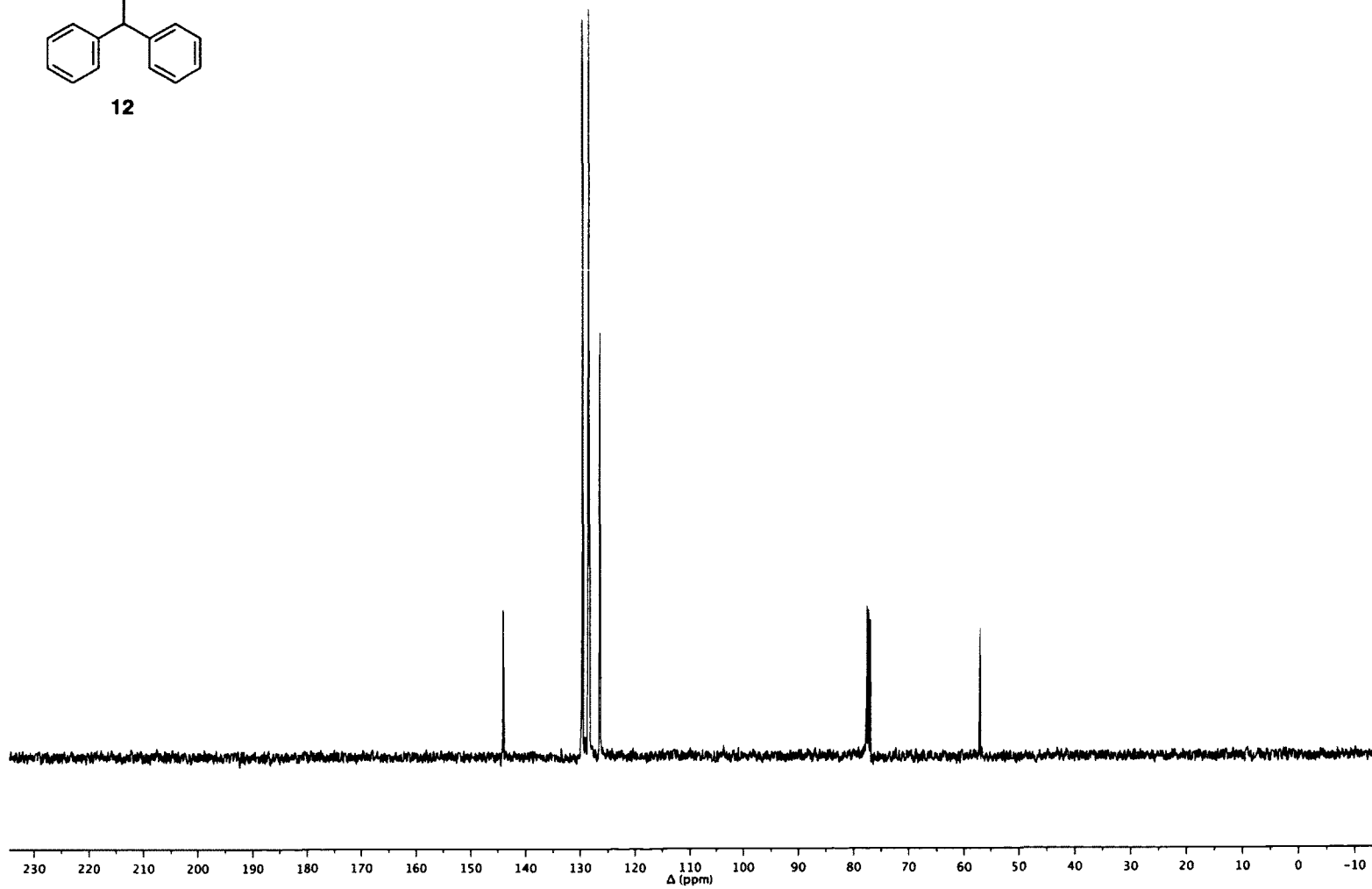
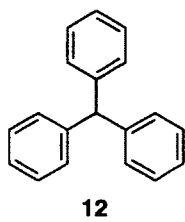


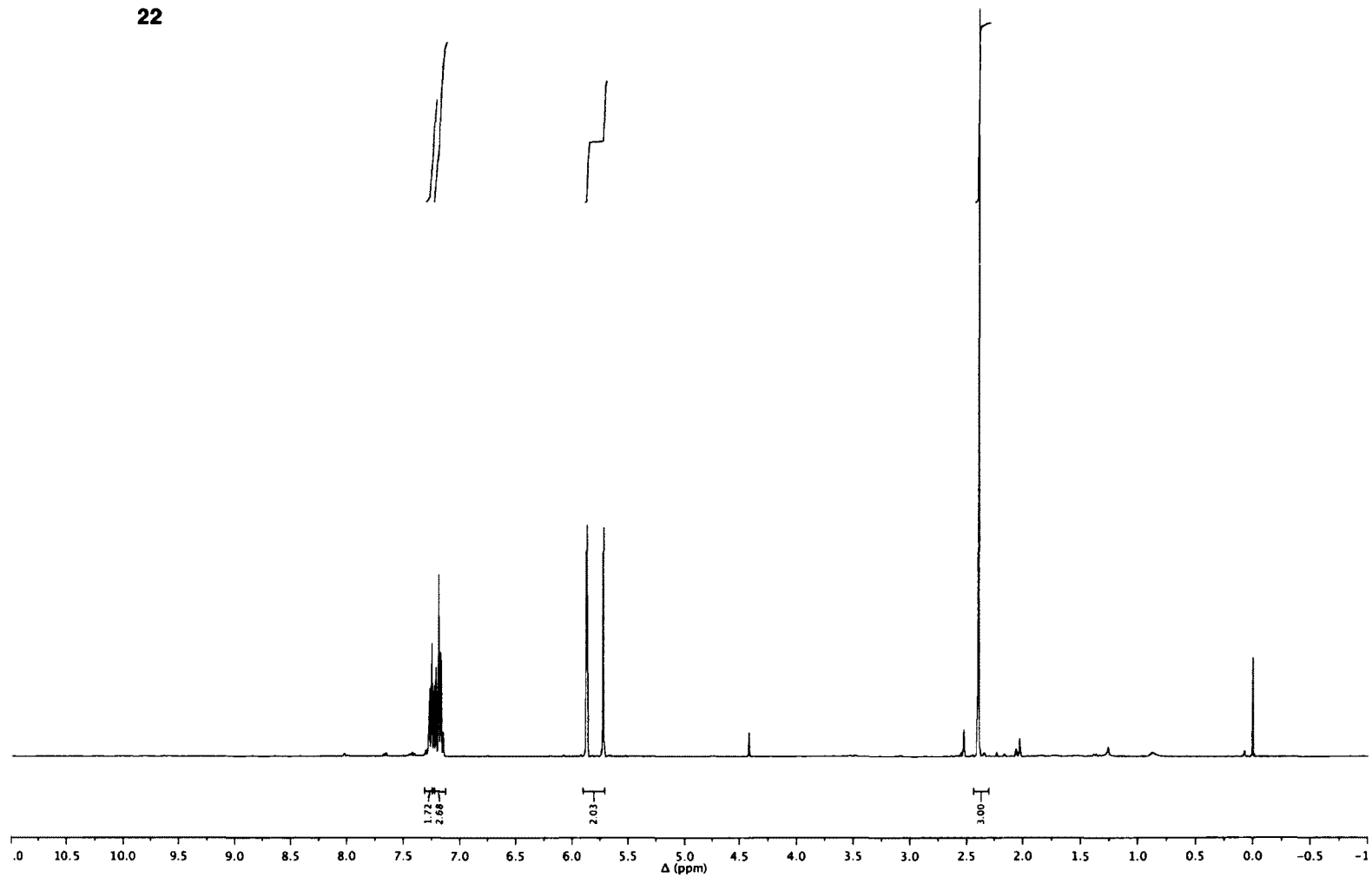
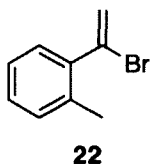


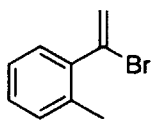




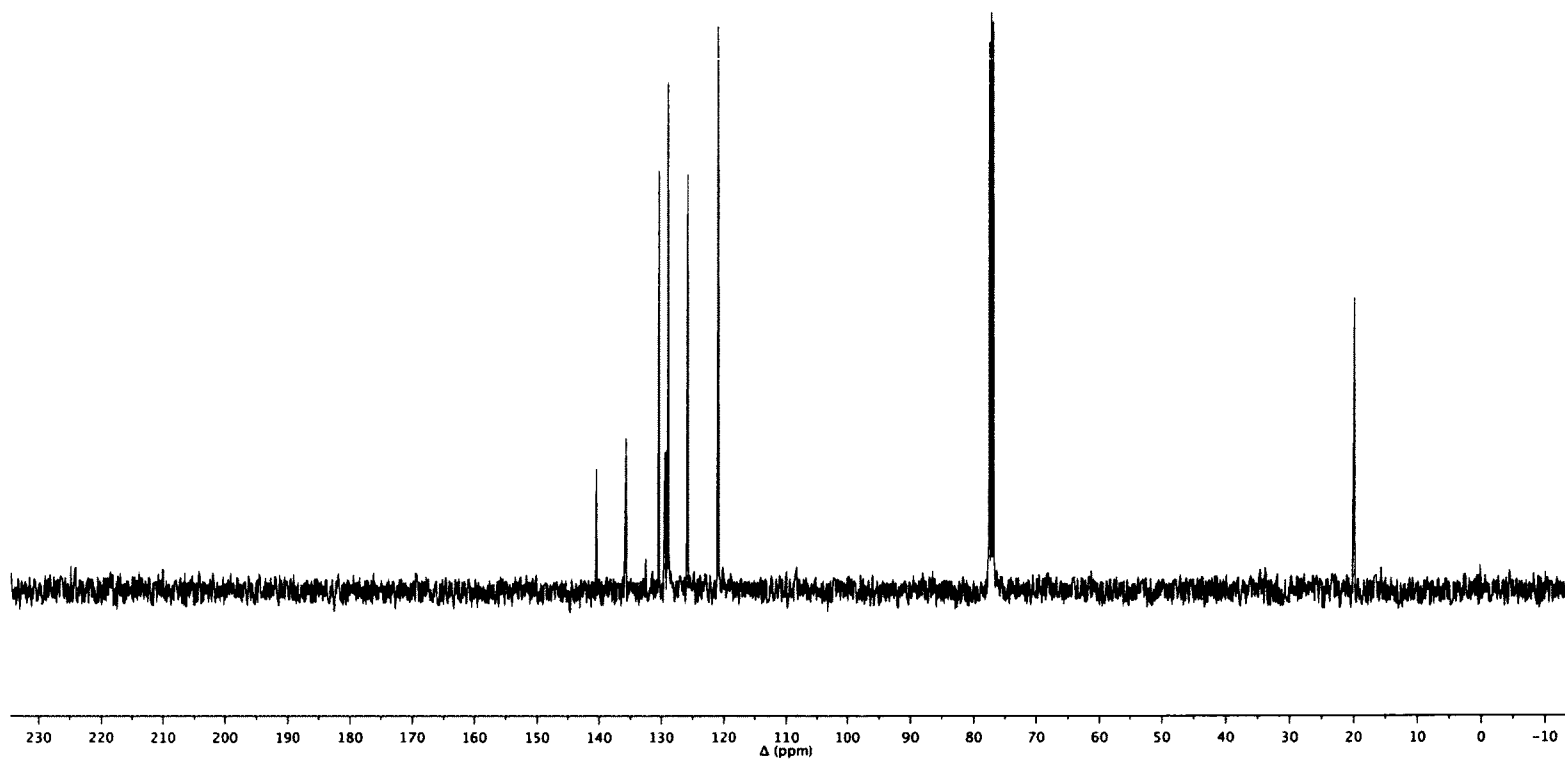


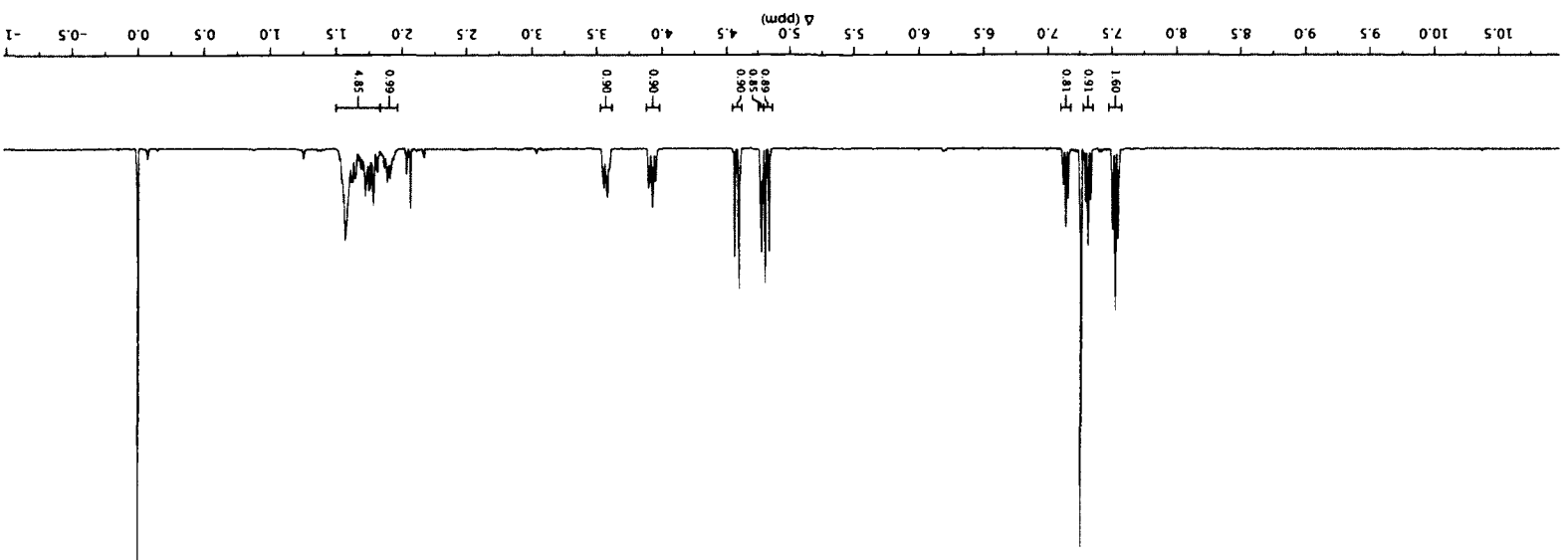
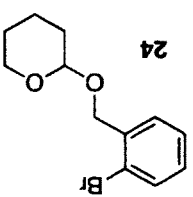


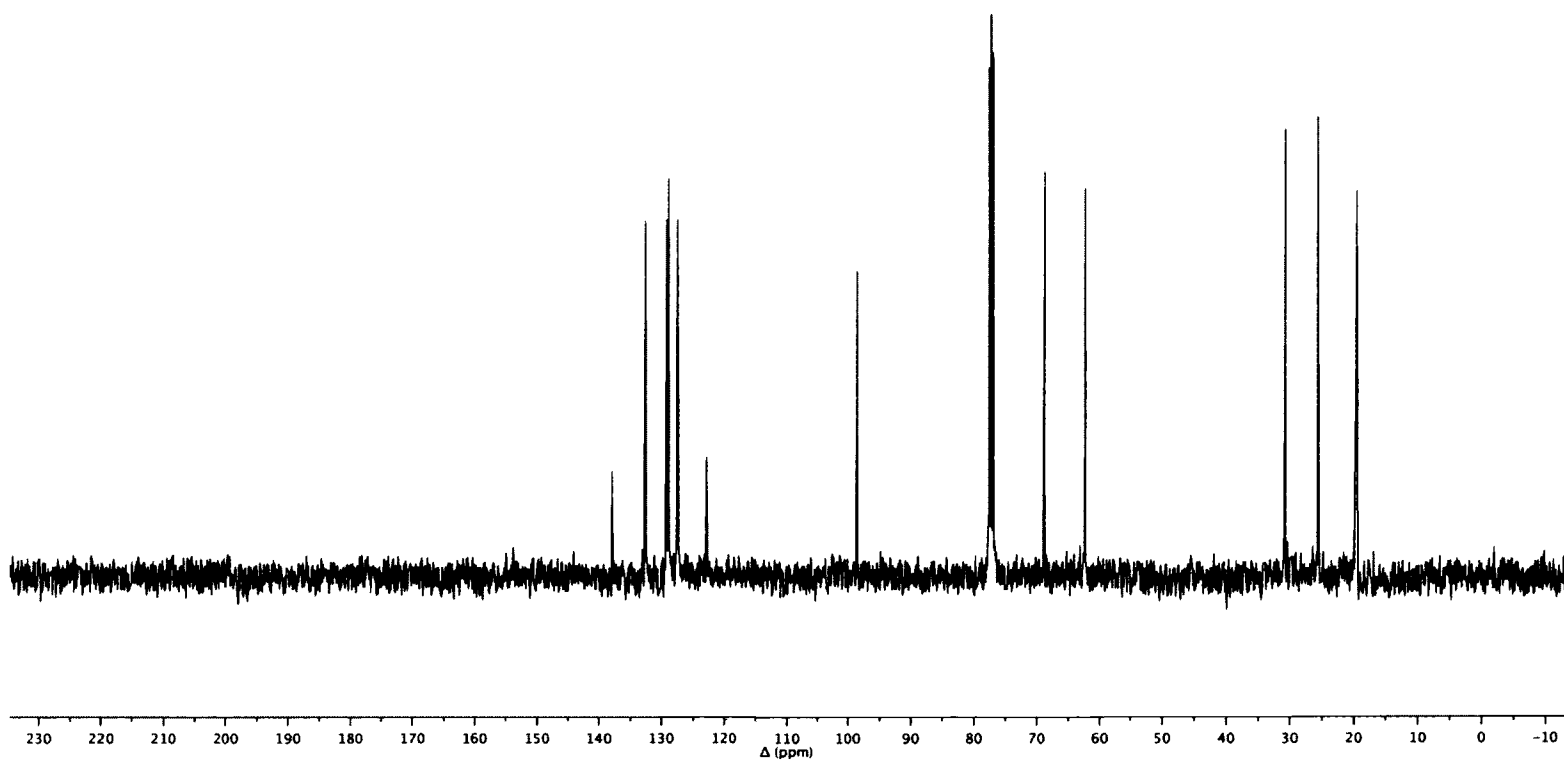
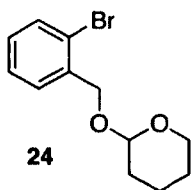


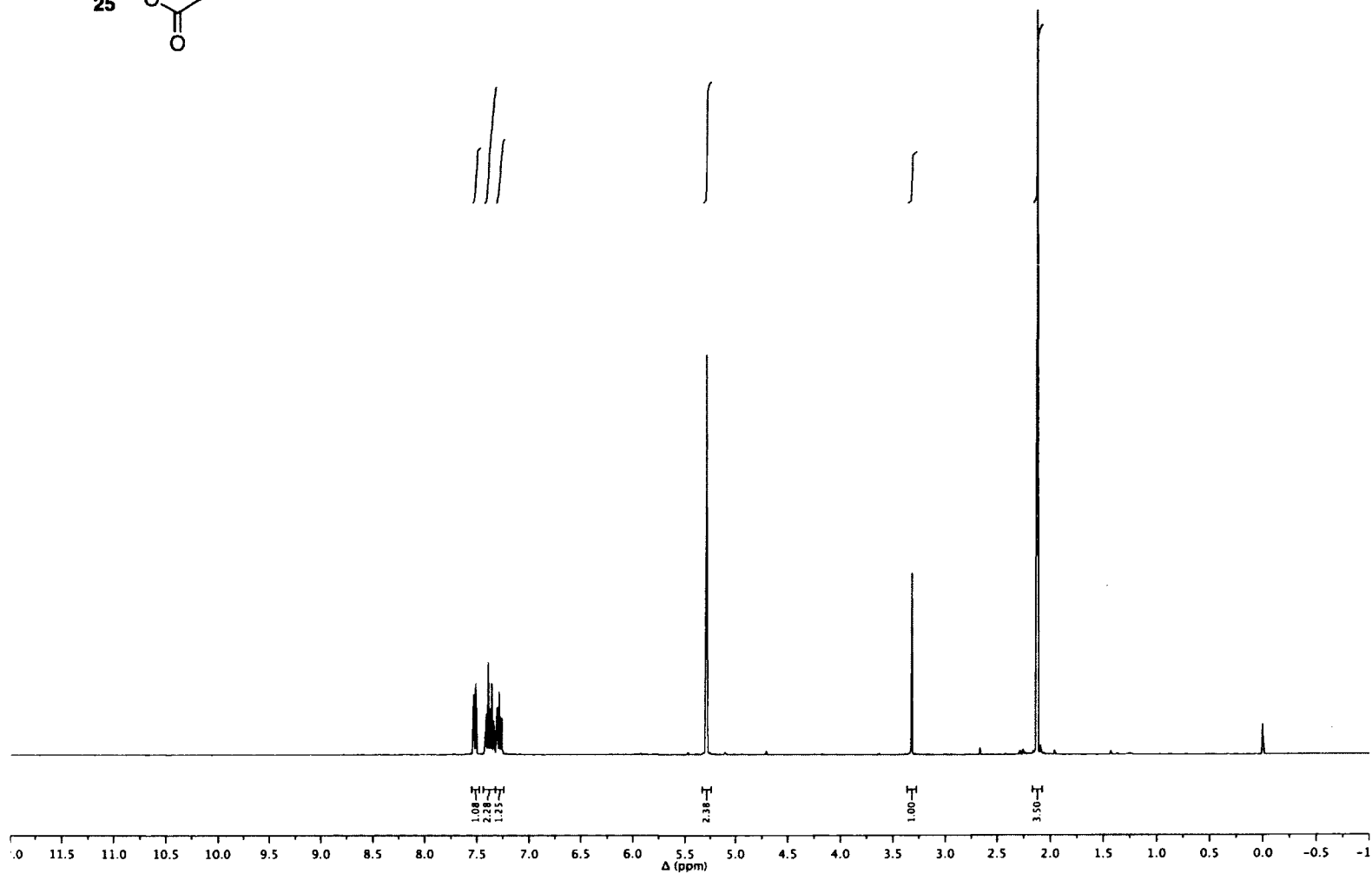
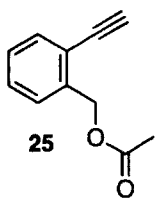


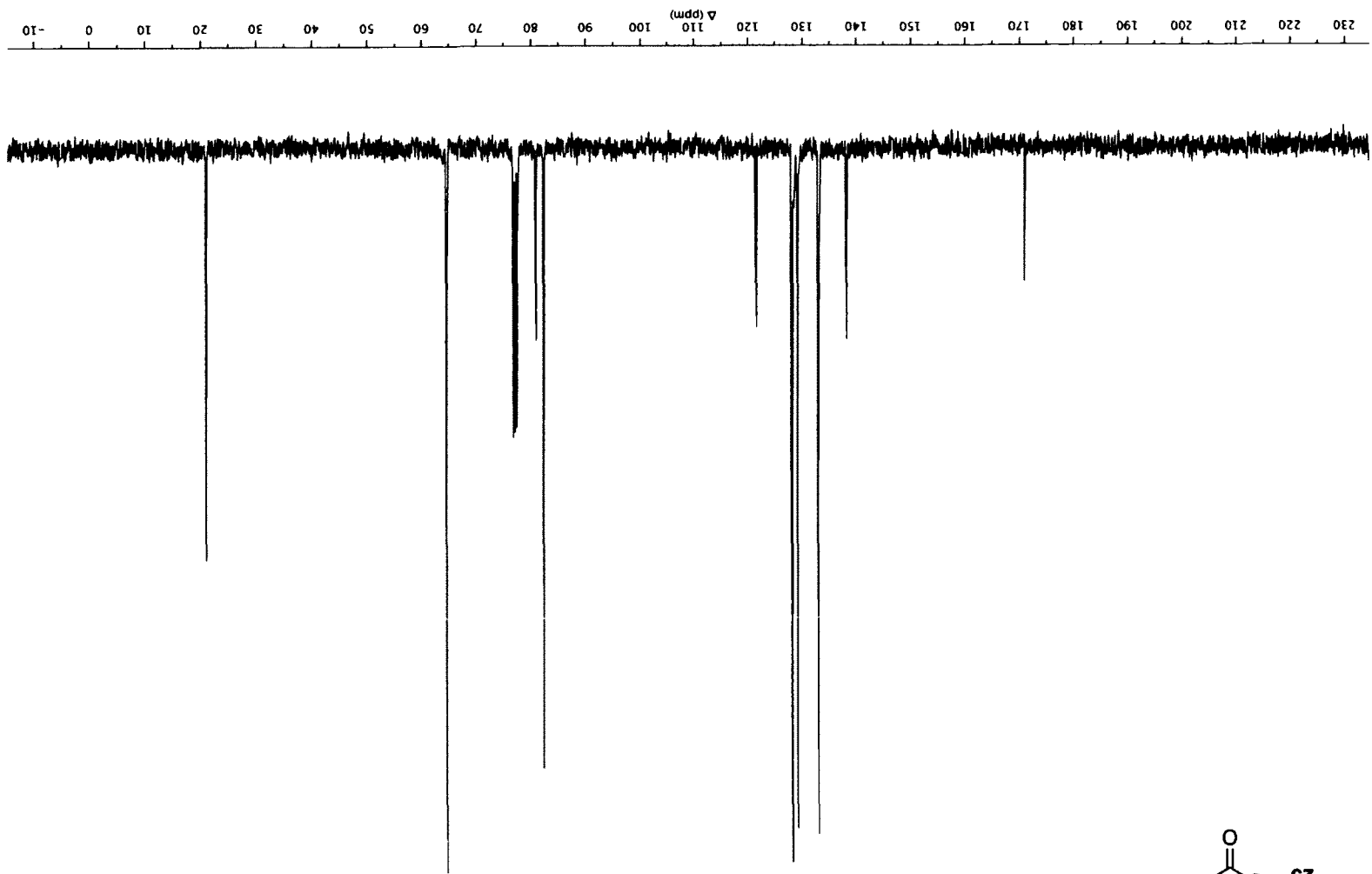
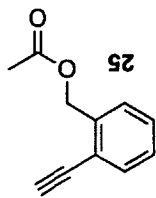
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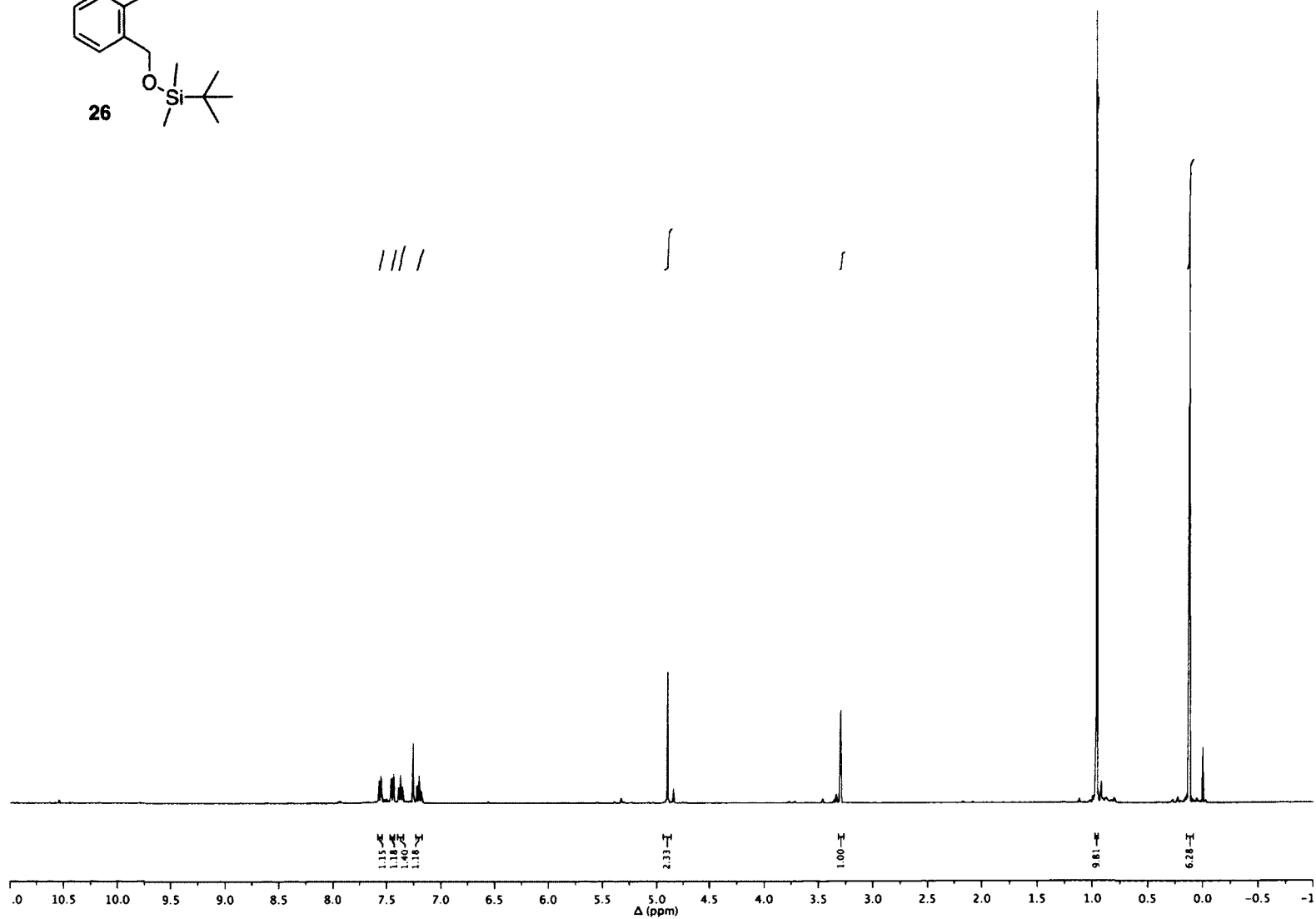
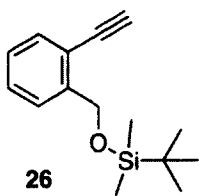


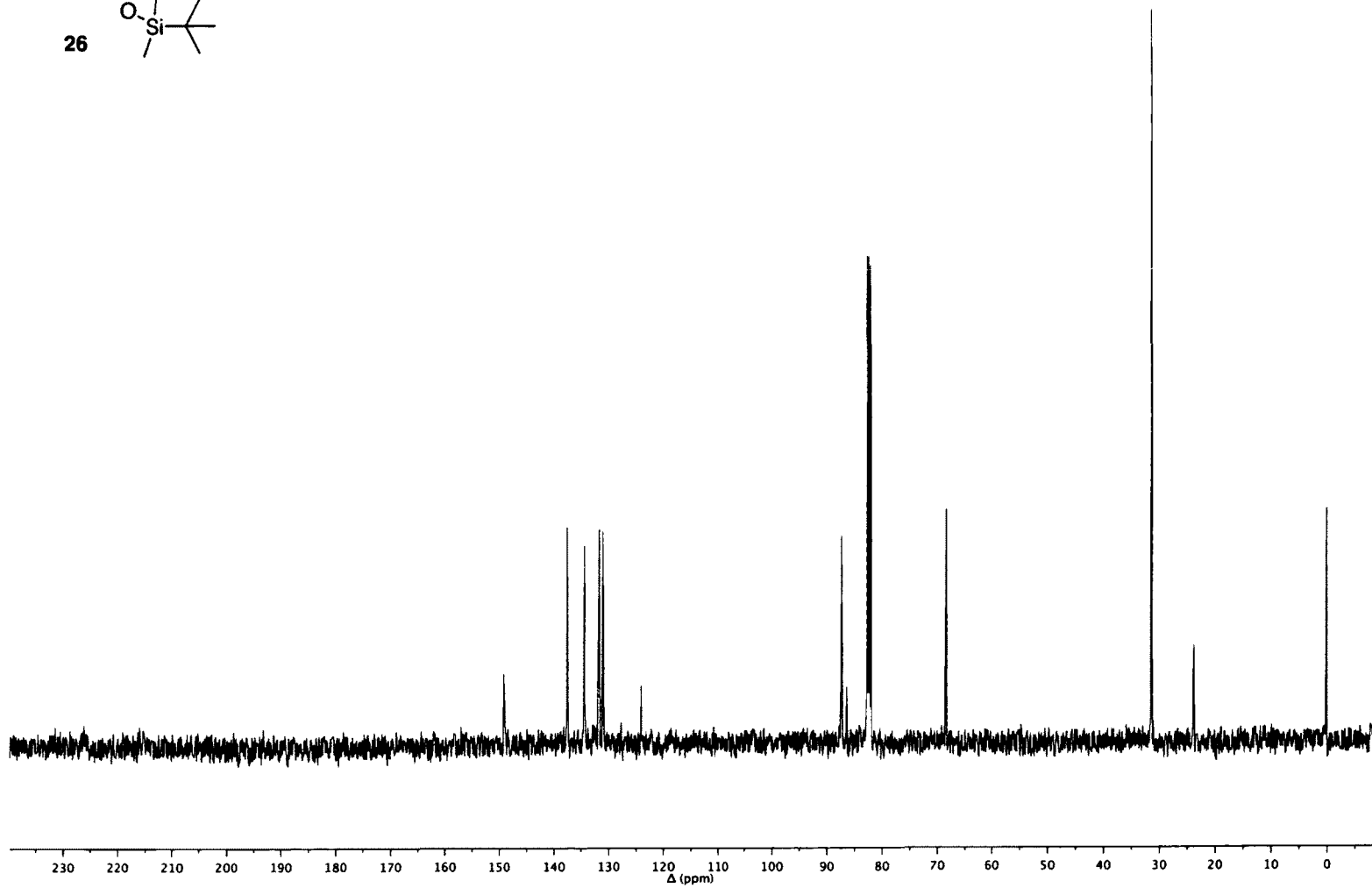
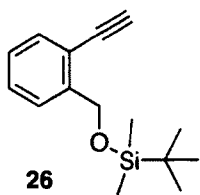


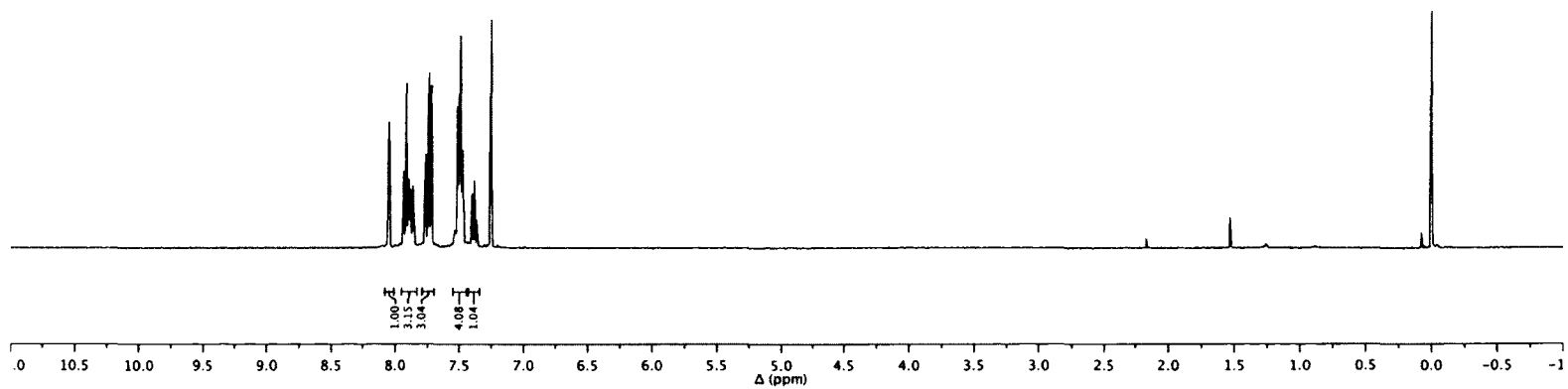
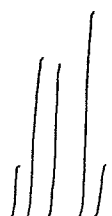
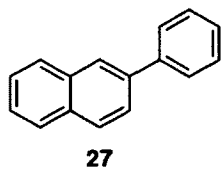


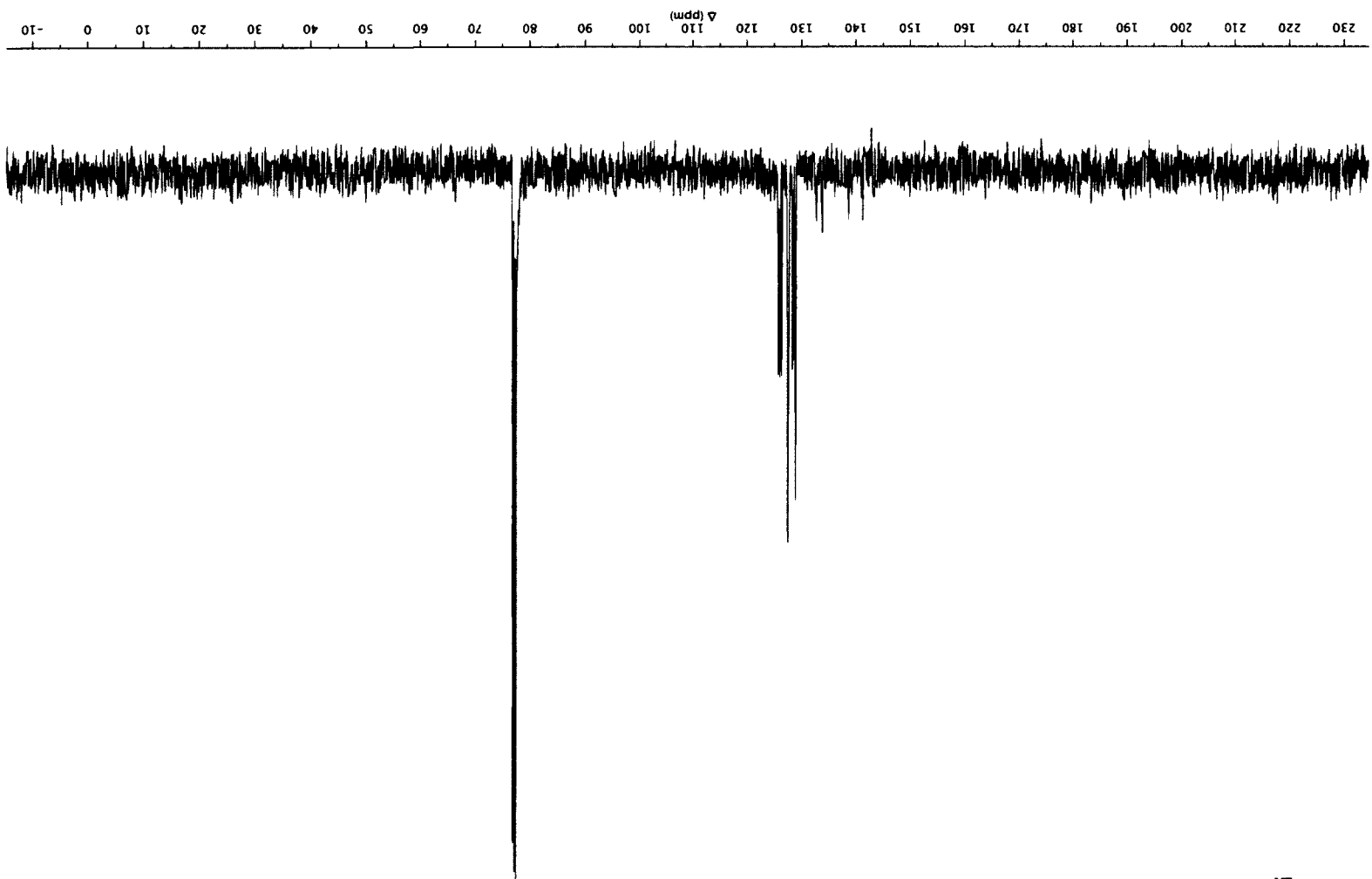
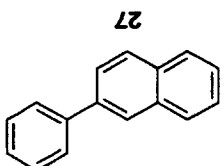


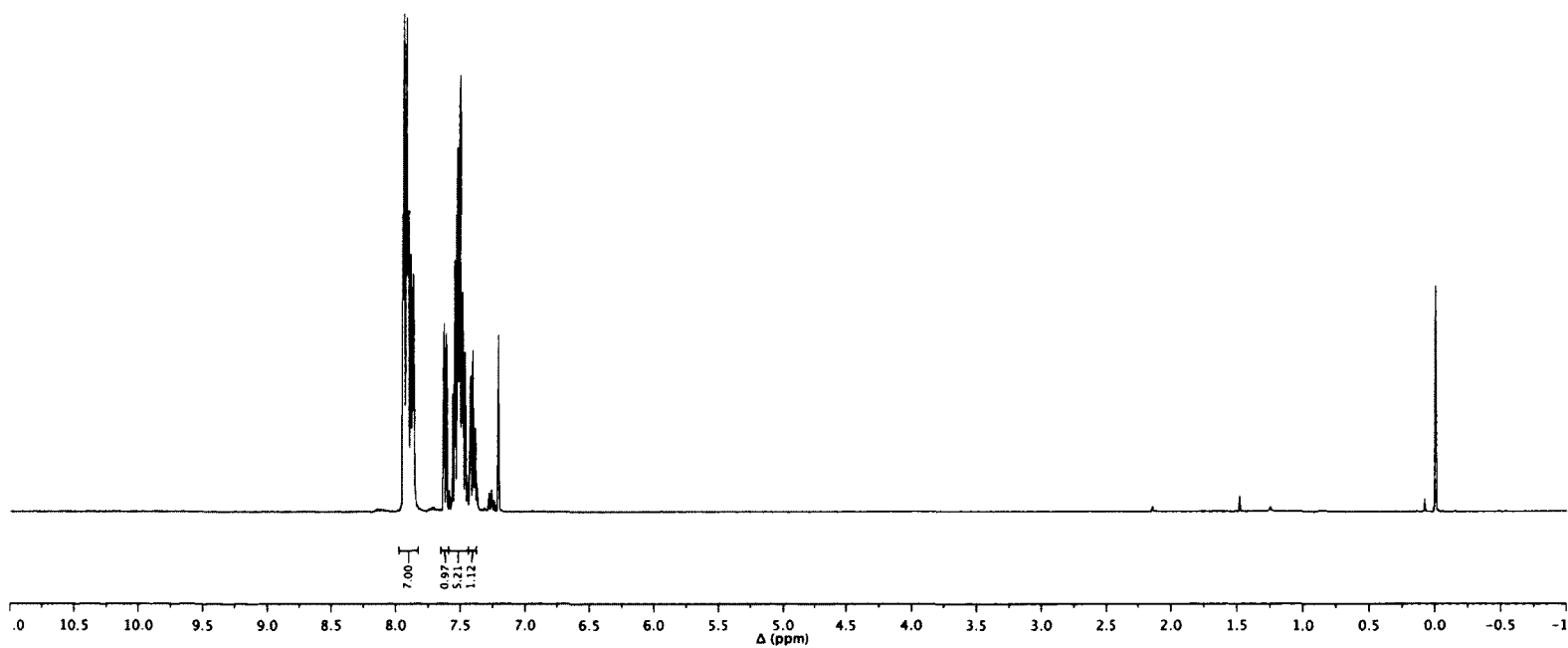
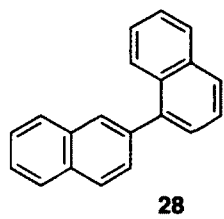


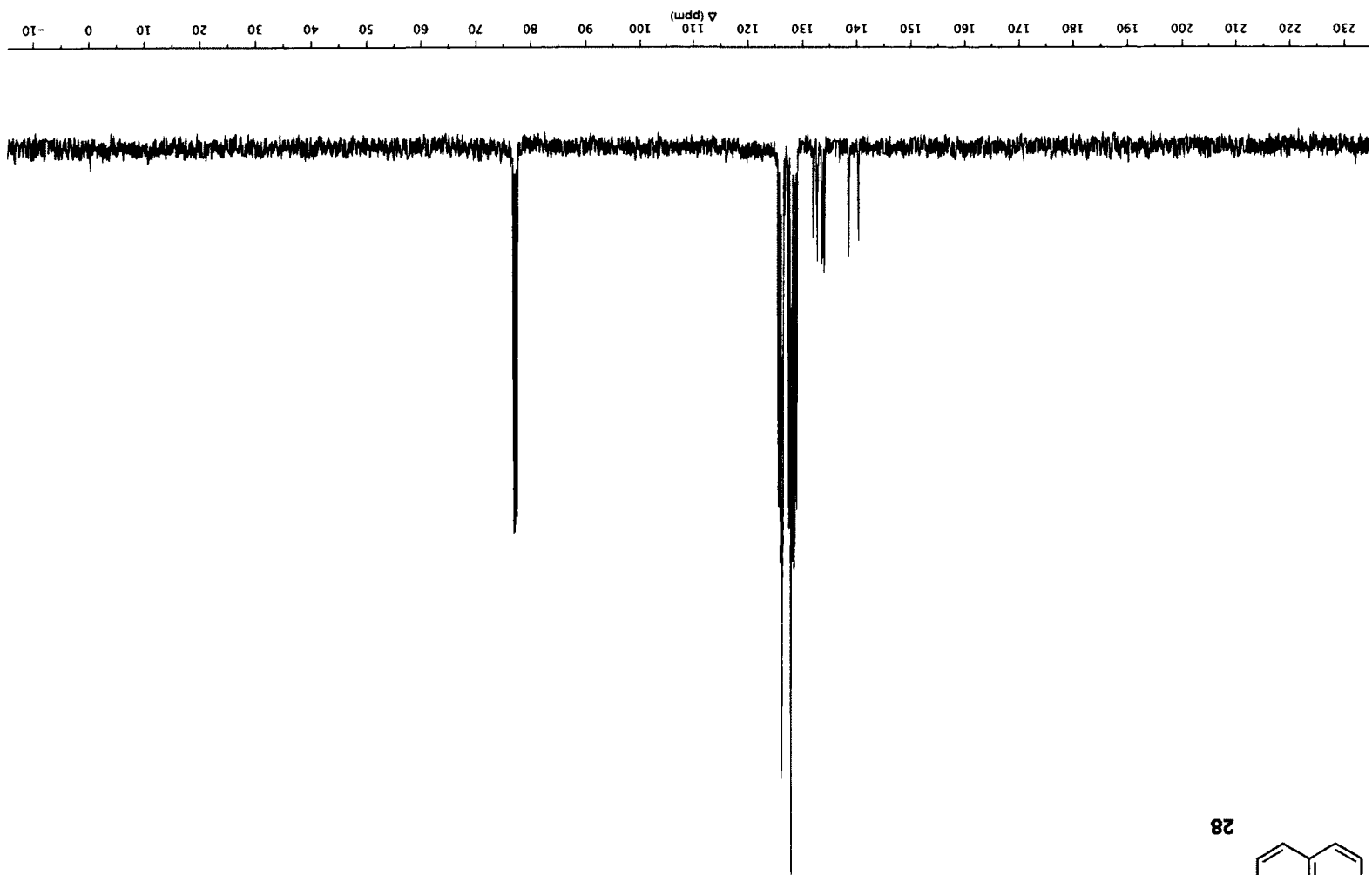
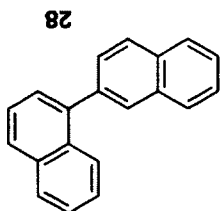


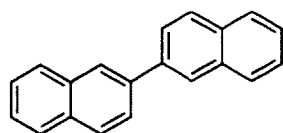












29

